GIS-BASED PAVEMENT MAINTENANCE MANAGEMENT MODEL FOR LOCAL ROADS IN THE UK

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I dedicate this thesis to the memory of “my beloved mother Fatma Alfar and my brother Riad Alfar”

And

To my dear father Yousef Alfar and my dear sister Intisar Alfar

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"The greatest glory in living lies not in never falling,
but in rising every time we fall"

"الأمجاد العظيمة في الحياة لا تكمن في عدم الوقوع، بل في النهوض بعد كل وقعة"

Nelson Mandela

ABSTRACT

Roads represent a major long-term infrastructure investment. A well-managed and maintained road is therefore fundamental to the safety and availability of the road network as a whole. In carrying out pavement maintenance functions, Local Road Authorities face growing pressures arising from inadequate budgets and greater accountability, when many of the existing roads have reached the upper limits of their design life spans while being subjected to increasing traffic.

There are many factors that influence the decision making process in pavement maintenance management, including road surface conditions, safety, traffic loading, cost, funding and prioritisation decisions, hence an efficient approach is vital to ensure optimisation and a satisfactory trade-off between conflicting factors.

A Multi-criteria Decision Making (MCDM) approach is used to handle the trade-off between conflicting factors. It is processed in the Analytical Hierarchy Process (AHP) using Excel software, and the database developed in Excel is then imported into GIS in order to allow ease of query, analysis and visualisation of results. The main key output of this research will be the development of a GIS-based pavement maintenance management model to support decision making in pavement maintenance management.

The most important factors influencing decision making in pavement maintenance management are established through a nationwide questionnaire survey, which is undertaken among the UK Local Authorities' pavement maintenance experts. 14 factors were identified, which are: Remaining Service Life, Road Condition Indicator (RCI), Type of Deterioration, Observed Deterioration Rate, Traffic Diversion, Importance of Road/Classification, Annual Average Daily Traffic (AADT), Possible Conflict or Overlap with Other Road Works, Risk of failure, Safety Concern, Accident Rate (related to surface condition), Scheme Cost, Available Budget/Funding and Whole Life-Cycle Cost. Interviews were also conducted with experts in pavement maintenance within different Local Road Authorities to justify the rated factors affecting pavement maintenance prioritisation.

The case study approach was adopted, based on Runnymede District roads within the Surrey County Council, for developing and testing the GIS-based decision support model. The output model was validated through interviews with four experts in pavement maintenance as target end-users, and the model was judged as a rational, simple and usable appropriate tool for network analysis as GIS. However, a risk of inadequate budgets might limit the practicability of the model.

Chapter One

Introduction

1.1 Background

It is known that the road network is the most prominent publicly used network that is operated and maintained by road authorities. The road network is used daily by people and is crucial in facilitating economic activity; in addition, it has an impact on the community. Therefore, an effective pavement maintenance management system (PMMS) is essential for the economic stability.

According to Kulkarni and Miller (2002), in the early 1970s, pavement maintenance management systems (PMMSs) were introduced and they have evolved continuously in terms of their scope, methodology, and application. Kulkarni and Miller (2002) described these systems by evaluating the past and current practices and identified future directions for the key elements.

The early systems evaluated and ranked pavement maintenance projects based on such factors as the current road surface condition (pavement condition) and traffic, where these systems were project-level systems to evaluate project priorities, and did not consider future pavement conditions, nor addressed network-level planning issues such as the limited budgets (Kulkarni and Miller, 2002).

In the early 1980s, the first system that considered the network perspective was developed for the Arizona Department of Transportation (Kulkarni and Miller 2002). However, systems which were developed again in the 1990s utilize integrated techniques of performance prediction, network-level and project-level optimisation, and Geographic Information Systems (GIS) (Kulkarni and Miller 2002).

A perfect maintenance scheme on road networks is one that keeps all sections at a sufficiently high level of functional and structural condition (Agarwal et al., 2004). Due to the increasing traffic on roads, a timely repair that is often critical is constrained by time, budget and other resource availability such as manpower and equipment. This makes a priority ranking scheme for the selection and scheduling of pavement sections for maintenance an essential dimension for study, and an integral part of pavement maintenance management systems (Fwa and Chan, 1993).

Effective pavement maintenance and management practices require the application of pavement management concepts and principles in order to maximise the benefit of the limited funding available annually for pavement maintenance, sustaining the availability and level of service of the road network and improving the overall condition of pavement.

There are many factors that influence the decision making process in pavement management including the prioritisation of pavement maintenance and funding, hence, identifying the factors affecting pavement maintenance prioritisation through the review of literature is the initial step in this research. Therefore, a Multi-Criteria Decision Making (MCDM) approach is necessary to ensure a satisfactory trade-off between conflicting factors and the optimisation of the results.

The intention of this research is to propose a rational approach that considers the most influential factors on pavement maintenance prioritisation for priority ranking of pavement maintenance within local road authorities. The work relies on GIS capabilities, particularly as a decision support tool. GIS is becoming more popular in transport engineering. It offers some special features including spatial analysis and visualisation that can enhance the approach to pavement management.

This research focuses on developing a GIS-based decision support model to assist decision makers with regard to pavement maintenance prioritisation. The model will be developed using roads from a selected case study (Runnymede District in Surrey), and validated through validation interviews with industry practitioners from different local road authorities.

1.2 Rationale of Research

Mobility is a very basic human activity. In the transport setting, mobility has shown positive effects on the economic advancement of a place, in as much as it is thought that accessibility and economic performance are closely related at local levels and on a regional scale (European Spatial Planning Observation Network, 2004). Given this, the demand for efficient transport systems is inevitable, urging road planners to examine how to keep roadways in a proper condition so as to satisfy public expectations. Some causes of transport inefficiencies associated with pavement maintenance are:

- The average daily traffic using the road network is above its capacity
- Lack of spatial information systems that can monitor the pavement condition
- Undefined pattern of surface deterioration
- No proper rating system used for prioritising maintenance
- Using the wrong methods for pavement maintenance treatment

Pavement condition was the conventional basis for deciding on a road section maintenance priority, with no adequate evaluation of other interrelated factors that also seriously influence the maintenance priority. This sort of assessment scheme is based on numerical condition indices that do not present all factors in a rational manner, nor reflect the importance placed on them by road authorities, and therefore do not have a sound physical meaning (Agarwal et al., 2004).

Crucially, a rational approach for priority ranking of pavement maintenance management for local road authorities is required since there are a number of factors to synthesise when deciding on section priority.

1.3 Research Questions

- What are the most significant factors that are taken into account in the prioritisation decisions for pavement maintenance works by local road authorities in the UK?

- How significant is using GIS to developing a decision support model that has multiple options for planning pavement maintenance works?

1.4 Aim and Objectives

1.4.1 Aim:

To develop a GIS-based decision support model to support the decision-making process in pavement maintenance management of the existing roads under the control of Local Authorities in the UK.

1.4.2 Objectives:

- To investigate the current pavement maintenance management practices, its principles and related challenges.

- To establish the most significant factors that influence decision making in Pavement Maintenance Management.

- To explore the best practices from real life and research on the methods of pavement maintenance management with GIS.

- To specify a conceptual model that employs a Multi-Criteria Decision Making (MCDM) approach for effective pavement maintenance management using GIS as a decision support tool.

- To implement the conceptual model proposed in the previous objective in GIS and to test the proposed model based on GIS via a case study of Runnymede roads in the Surrey County Council.

- To validate the implemented model via validation interviews with industry practitioners from different local authorities.

1.5 Outline Research Methodology

This research is based on a mixed methods approach, which involves both qualitative and quantitative methodologies. The adopted research methodology therefore comprised the following main components:

- The major thrusts of the research were the identification of the most effective prioritisation factors in pavement maintenance, and the development and testing of a GIS-based decision support model.

- The main research is based on the case study approach for developing and testing a GIS-based decision support model.

- The research started with a review of the existing literature concerning the concepts and practices of network pavement maintenance, the existing pavement management practices generally and within local road authorities particularly, and GIS methods. The literature review of each element can be found within the relevant Chapter dealing with each aspect.

- The core data collection techniques adopted for the research are a questionnaire survey amongst local road authorities' practicing road engineers and managers; interviews with specialists in pavement maintenance from different local road authorities; and a case study (Runnymede District roads in the Surrey County Council).

1.6 Ethical Considerations

"Code of Practice for Research: UK Research Integrity Office" is adopted as the code of ethics guidance for this research, and ethical approval was obtained from the ethics panel in the University of Salford as ethical considerations were outlined below:

- Local Road Authorities' pavement engineers and managers will be approached by e-mail so as to have the purpose of this research explained and survey questionnaires distributed. The relevant e-mail addresses will be found through the "Road Maintenance Annual Handbook", which includes all the UK local road authorities' contact details.

- All participants will be provided with research information in written form, and participants will then sign a consent form stating their agreement to participate. In addition, participants will be informed of their right to withdraw from the study at any time without any justifications.
- In conducting interviews, anonymity will be assured and the identity of the participants will be protected, unless the participant wishes to be named and

thanked in the acknowledgements of the thesis. Participants stating their agreement to participate will sign a consent form.

- In terms of data protection regarding data obtained through the surveys, interviews and case study, data will be stored on a personal computer, on a university computer and on a USB stick. In order to access the stored data, a password is needed for the university computer and for the USB stick, and a fingerprint is needed to access the personal computer. In addition, in order to access the document where the data is saved, a password is needed.

- Data will be used for academic research purposes only.

1.7 Contribution to Knowledge

This research contributes to knowledge by achieving the following outputs:

- Establishing the most significant factors affecting pavement maintenance prioritisation in local road authorities;
- A GIS-based decision support model for use in pavement maintenance management, where the most significant prioritisation factors adopted are based on a general consensus amongst local road authorities.

1.8 Research Scope and Limitations

The scope of this research is first to assess the current pavement maintenance management practice in local road authorities in the UK. Although there may be scope in some generalisation, there is a limitation of the research in that the assessed pavement maintenance management practices are for the most part only applicable to local authorities who are responsible for their own roads.

The use of GIS as a decision support tool for prioritisation has wider implications and scope, particularly since the factors adopted in the design of the model are based on a general consensus amongst road managers and practitioners in local road authorities.

1.9 Structure of the Research Thesis

Chapter One: Introduction

This chapter will introduce the research project by first giving background details to the research topic and presenting the rationale of the research and research questions. The chapter then will present details of the research aim and objectives, followed by the research methodology, contributions and research scope and limitations.

Chapter Two: Literature Review – Existing pavement maintenance management practices

This chapter will present a review of the literature describing the current and most recently adopted methods in managing the pavement maintenance by local road authorities in the UK. The chapter will then draw attention to some of the limitations and weaknesses arising from the current pavement maintenance management approaches.

Chapter Three: Best practice methods of pavement maintenance using GIS

This chapter will review the literature relating to the use of the GIS technique in the context of pavement maintenance prioritisation and decision support. The rationales behind the selection of GIS will then be discussed.

Chapter Four: Research design and methodology

This chapter will describe the research methodology adopted in this study, in order to fully explore the research aim and objectives and address the chosen research design. The chapter will start with a review of the literature on the theory and practice of the research strategies, methods and qualitative and quantitative data analysis techniques employed, together with their main components. Alternative research methodologies will also be discussed and their advantages and disadvantages will be outlined. The selected methodology will then be described along with the reasons for this selection in the context of the stated aim and objectives of the research.

Chapter Five: Impacting factors of pavement maintenance via questionnaire based survey

This chapter will first describe the processes of planning and undertaking the questionnaire survey within the UK local authorities, which was implemented in order to establish a general consensus amongst local road authorities' practicing road engineers and managers, as to the most significant factors affecting pavement maintenance prioritisation decisions. This will be followed by a presentation of the data analysis and processing of the data generated from the survey responses to finalise the most significant factors taken forward for the GIS model development.

Chapter Six: Conceptual model of the proposed pavement maintenance approach

This Chapter will present the conceptual model of the proposed pavement maintenance approach. The specifications of the proposed model supporting decision makers will be described and discussed. First, a description of the functionality of the model is provided in order to justify its proposed application, followed by an outline of the data requirements of the model and its structure. The components of the model will be presented, and then the proposed model will be illustrated from a conceptual point of view.

Chapter Seven: Prototype development of the model in GIS

This Chapter will present the development of a GIS model to be utilised as a decision support tool in pavement maintenance prioritisation. A prototype model will be developed for a case study of Runnymede roads within the Surrey County Council. A formula for obtaining the Pavement Maintenance Priority Score (PMPS) will be developed, which will be the base for ranking the alternatives. Thereafter, joining data in GIS will be performed to implement the model.

Chapter Eight: Validation of the model

This chapter will present the evaluation of specialists in pavement maintenance on the implemented GIS-based pavement maintenance management model using SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis.

Chapter Nine: Conclusions and Recommendations

This chapter will set out the main conclusions derived from this research relating to the decision support system and the suitability of the GIS model for the case study as well as the extent to which the results could be extrapolated to other local road authorities. The conclusions will be structured around the achievement of each of the stated objectives of the research, and will describe how each objective was accomplished through the relevant research stage.

The chapter will then present specific sections dealing with the research limitations, and will describe and discuss the original contributions of the research. Ultimately, it will make recommendations for future research in this field.

Chapter Two

Literature Review: Existing Pavement Maintenance Management Practices

2.1 Introduction

Pavement maintenance plays an important role in the management of road networks in the United Kingdom as well as other parts of the world. The quality of pavement in roads significantly affects travel, and poor conditions put people's safety at risk (World Bank, 2011). Over time, the strength and quality of pavements deteriorate due to the impact of pressure on surfaces from heavy loads as well as the elements. "Roads deteriorate due to traffic usage, weather conditions and the need for utility companies to lay and maintain their equipment" (Surrey County Council, 2015). For these reasons, pavement maintenance has become an important aspect of highway management and infrastructure development in the field of transportation. In this chapter, the main focus is on pavement maintenance management in the UK.

The succeeding discussion is divided into different sections. First, road length statistics, types of local authorities and general pavement maintenance practices will be discussed, along with existing pavement data records and pavement inspection and monitoring practices. Second, pavement maintenance management practices will be explored within the context of UK local road authorities including pavement condition assessment and pavement maintenance management systems. The major issues that are affecting pavement maintenance management will also be discussed in this chapter. Third, limitations and shortcomings in the existing pavement maintenance management practices in local authorities will be discussed. Fourth and fifth, the function and role of Surface Condition Assessment for the National Network of Roads (SCANNER) and the UK Pavement Management System (UKPMS) in pavement maintenance management will be discussed. The factors affecting pavement maintenance prioritisation in the UK will also be discussed in this chapter.

2.2 Road Length and Types of Local Authorities in the UK

It is difficult to ascertain a reliable figure of the total road length in the UK. However, the total road length in the UK in 2012 was estimated to be 409,762 Km (Highlec, 2012). The largest proportion of the total road length in the UK was in England, and was estimated to be 293,346 Km, followed by Scotland 55,886 Km, Wales 34,974 Km (DfT, 2013 and Highlec, 2012) and Northern Ireland 25,556 Km (DRD, 2015). Table 2.1 below illustrates the detailed road length in the UK.

	Road Length (km)	**No. LAs**
England		
CCs	172,551	30
MBCs	40,757	36
LBs	13,643	33
Unitaries	57,109	52
HA & TfL	9,286	14
Total England	**293,346**	
Scotland		
Unitaries	52,386	
Scottish Exec	3,500	
Total Scotland	**55,886**	33
Wales		
Unitaries	33,265	
National Assembly	1,709	
Total Wales	**34,974**	25
N Ireland		
Total N Ireland	**25,556**	4
Total UK	**409,762**	
LA= Local Authority; CC= County Council; MBC= Metropolitan Borough Council; LB= London Borough; HA= Highway Agency; TfL= Transport for London		

Table 2.1: Detailed Road Length in the UK (Highlec, 2012)

Different local authorities have the responsibility for the local road maintenance in the UK. London Borough Councils, Metropolitan District, County or Unitary have the responsibility for local road maintenance in England. However, some County Councils, which have agreements with the Highway Agency, provide highway maintenance services (UK Roads Liaison Group, 2005).

Unitary Councils provide local road maintenance in Scotland and Wales. However, the Roads Service of the Department for Regional Development (DRD) provide local and national maintenance in Northern Ireland. (UK Roads Liaison Group, 2005).

2.3 General Pavement Maintenance Practices

Pavement management can be described as the process of planning, organising and controlling all works on the roads considered necessary to sustain a required level of service or improve the overall condition of the roads to attain a certain desired level of service. The process encompasses the integrated activities of inspection, monitoring, testing, assessment, maintenance, repair and renewal. Pavement management needs to be adequately funded in order that all the identified defects are undertaken in a timely manner, and the work should be coordinated to maximise the potential outcome from the available funding and other resources.

Generally, pavement maintenance practices refer to activities and practices through which public transportation agencies manage the construction of road surfaces (UK Roads Liaison Group, 2005). Pavement maintenance encompasses strategic planning, design, monitoring or assessment, and the actual implementation of maintenance practices after a set period of time. During strategic planning and design, public agencies in charge of transportation identify pavement needs and target areas, as well as the construction operations and materials that will be used. After laying out pavements, public agencies will then continue monitoring existing pavements to detect damages and other problems that necessitate immediate attention. Pavement maintenance procedures will then be applied to address the damage. One important aspect of pavement maintenance is prevention (UK Roads Liaison Group, 2005).

The Department for Transport (DfT) published a document regarding the responsibilities and duties of local road authorities and illustrated that generally, in England, local road authorities are responsible for the management of local roads. Under Section 41 of the Highways Act 1980, road authorities have the responsibility of the road network maintenance in their area. However, the assessment of the road network and defining which parts are in need of repair is the decision of each individual authority, based upon their circumstances. The Department for Transport has no rights to intervene in local decisions on such matters (DfT, 2012a).

Pavement maintenance falls under three types: preventive, corrective, and emergency. In preventive maintenance, the main objective is to extend the life span and functioning of pavements to prevent immediate damages. To accomplish this objective, public agencies implement special treatments on pavement surfaces as a way to slow down degradation or damage and thereby reduce the need for maintenance procedures. Corrective maintenance refers to activities following the damage of pavement. Corrective maintenance may be needed when there is a loss of friction in roads, when potholes are forming, and when cracks or other types of damage are observed. Unlike preventive maintenance, corrective maintenance is a more reactive approach to preventing surface damage and reducing repairs needed for pavement. Emergency maintenance, on the other hand, takes place when there is an immediate need to repair pavements. Some potholes may require immediate attention when they affect traffic or may lead to accidents. In most cases, emergency maintenance practices are temporary measures taken until there can be permanent solutions performed to address the existing problem (Johnson & Snopl, 2000).

Critical elements affect the efficiency and success of pavement preservation. Some of these elements include the state or quality of the roadway, the cause of the problem, the appropriate treatments, the time needed to complete the preventive maintenance, and the outcomes of performance after assessment. All of these elements must be considered in implementing pavement preservation (Johnson & Snopl, 2000). Examples of preventive maintenance procedures may include sealing cracks or chips, filling in ruts or potholes, and applying overlays with thin consistency. New technologies also contribute to pavement maintenance. Examples of technologies include ultra-thin wearing courses, overlays with thinner than average consistency, and micro-surfacing applications (Johnson and Snopl, 2000).

Efficient preventive maintenance of pavement must be part of a thorough long-term plan. Preventive measures may be taken even before damage materialises on road surfaces. In this way, local authorities may prolong the life span of pavements and reduce the need to make repairs. Furthermore, preventive maintenance should be done regularly to reduce damage, the need for repairs, and spending on repairs as much as possible. The "periodic renewal of the pavement surface can provide several benefits, including sealing the pavement surface, and controlling the effects of oxidation, ravelling, and surface cracking" (Johnson and Snopl, 2000).

Pavement preservation also requires different elements, including adequate education, the right philosophy, appropriate timing, and funding. Local authorities must be made aware of preservation policies and practices. In addition, local authorities, for instance, must understand the relevance or importance of implementing preventive measures. The right philosophy refers to a shift in thinking, which involves the prioritisation of prevention. During earlier times, public agencies or governments failed to prioritise prevention. This led to frequent infrastructure development and construction, as well as spending. In recent years, however, there has been a shift in prioritisation as various agencies realised the importance of focusing on prevention rather than construction. Pavement preservation also necessitates adequate and appropriate timing, as well as funding (Johnson and Snopl, 2000).

Pavement Management Systems (PMS) refers to "a tool or method that assists in optimizing strategies for providing and maintaining pavements in a serviceable condition over a given period of time" (Johnson and Snopl, 2000). Adopting and implementing management systems are highly important in ensuring that planning and implementation will make use of cost effective procedures, operations, and materials. Without the integration of management practices, pavement maintenance may be disorganised and fail to address existing problems efficiently. Part of PMS is pavement rating. Through pavement rating, local authorities may measure or assign numerical scores to the quality or state of pavements. After identifying or determining problems in pavements, public agencies would then have to determine the best possible treatment for problems or concerns. Different types of treatments include seals or materials to fill in cracks, micro-surfacing, overlays, and patches for potholes (Johnson and Snopl, 2000).

In the UK, pavement maintenance is guided by a code of practice. "Well-Maintained Highways" refers to a code of practice that guides maintenance management in highways. "Well-Maintained Highways" falls under the government's transport policy, specifically the transport management guidance. Furthermore, it is one of the series of codes of practices alongside "Well-Lit Highways", "Management of Highway Structures", and the "Management of Traffic Management Systems" (UK Road Liaison Group, 2005). Local authorities use this code of conduct as a guide "on highways management in an ever changing environment, creating a strong foundation for a positive and lasting maintenance policy" (UK Roads Board, 2011). It is expected that adopting and following the abovementioned code of practice will help local authorities in bringing about best value services for people in the community.

2.3.1 Existing Pavement Data Records

In order to understand the maintenance needs of pavement properly, as much knowledge of the pavement's data details as possible is required, where data should be accurate and reliable. However, in general, many of the local authorities may have reliable existing records, and although some of the existing records might have been accurate at the time of the assessment of the pavement, important changes in data might not have been recorded, where the maintenance works take long time to proceed.

Data records play an important role in pavement maintenance management because they provide relevant and significant information about road and pavement conditions. Essentially, data records not only inform the public about the government and local authorities' projects and initiatives to maintain roads, but also help authorities identify problem areas that necessitate immediate attention. With limited data, local authorities would be unable to arrive at correct and expected outcomes, as well as comply with standards of asset management (Aggregate Industries Ltd., 2015).

Asset management provides relevant data that guides pavement maintenance management. Asset profiles, for instance, help the government and local authorities optimise expenditure. Profile types may include the condition of assets, expenditure per assets, information about past defects and emergency repairs, history of claims, and results of inspection. Asset condition is derived from data within the Pavement Management System (PMS) as well as from the Highway Management System (HMS), results of surveys, inspections, and customer reports. Management information systems, on the other hand, provide information about expenditures per asset and reported defects and emergency repairs in the past (Leicestershire City Council, 2004).

The government has adopted the Building Information Modelling (BIM) as part of its initiative to establish standards in construction and maintenance until 2016. The BIM mandates the government and local authorities' partners, particularly those in the supply chain, to collaborate and provide significant and relevant information about construction and maintenance procedures (Aggregate Industries Ltd., 2015).

Through the BIM, local authorities may utilise a laying technology that improves existing and upcoming records. “The main driver for this development was to reduce the number of personnel in the immediate working area to improve safety and to provide real time information to operatives to improve the quality of the newly laid pavement” (Aggregate Industries Ltd., 2015). At present time, BIM allows the Highways Agency to gather the following types of data:

- Condition
- Date Laid
- Layer
- Material
- Notes
- Pavement Class
- Thickness

(Aggregate Industries Ltd., 2015)

Shaaban and Nadeem (2015) conducted a study on professionals’ perception towards using BIM in the highway and infrastructure projects. The perceived benefits of BIM for civil engineers on the highway and infrastructure projects include but are not limited to easily predict the performance of projects before they are built; respond to design changes faster; optimise designs with analysis, simulation and visualisation; and deliver higher quality construction documentation (Shaaban and Nadeem, 2015).

Shaaban and Nadeem (2015) identified visualisation as the top benefit of using BIM in highway and infrastructure projects followed by better communication between different disciplines, cost reduction, time saving, and sustainable design. The top challenge facing the implementation of BIM on highway projects was the resistance of practitioners to change their current practice. Other challenges reported by professionals included the need for additional investment in the software and hardware and the lack of the technical support (Shaaban and Nadeem, 2015).

However, it seems that there is a great future for BIM and once implemented on some of the highway projects in the future, it would be beneficial to evaluate the actual benefits and challenges.

Transport Scotland (2012) has provided data regarding pavement roadworks and travel delay costs. Based on Transport Scotland's report, pavement maintenance incurs costs as well as delays on the road. Transport Scotland obtained scheme data, which is an estimation of the area of work for different types of treatment during the past decade. Treatment types that were assessed include reconstruction, strengthening, and surface treatment. Based on the data obtained, surface treatment and reconstruction are the most common treatments applied in pavement maintenance operations. Furthermore, an increase in budget for maintenance also increases the number of maintenance operations. If budget decreases, there would also be a reduction in the number of maintenance operations, and, therefore, disruptions throughout all road networks (Transport Scotland, 2012).

UK Road Liaison Group (2005) identifies the purpose of data and information as tools to support the various functions of pavement management. These functions include inspection, assessment, planning, maintenance and repairs. The Code though distinguishes essential data and information records as those required to permit the local road authorities to carry out their statutory obligations under the Highways Act 1980, such as to protect the road network users and safeguard the authorities against legal action resulting from unsatisfactory management.

The foregoing discussion illustrates the existing data available online. Pavement data records are available via the official website but it cannot be accessed. Although the discussion does not explicitly show data, it reflects the types of data that are needed in decision making as well as some information about pavement maintenance. Furthermore, this section illustrates the important aspects of data that must be collated or obtained to guide decision making when it comes to pavement maintenance and management.

2.3.2 Pavement Inspection and Monitoring

Because of the costly and highly disruptive consequences of pavement deterioration, pavement inspection is a vital part of the overall maintenance and management of pavement. Pavement inspection must be undertaken systematically and not just if or when there are problems, and it also has an important part in the assessment of pavement by providing the necessary, as existing data for carrying out a meaningful assessment of the current condition.

Pavement inspection and monitoring is conducted via a structural condition assessment. "A pavement structural investigation is normally carried out to identify which pavement layers have deteriorated over time" (Transport Research Laboratory, 2015). Through structural assessment, local authorities may determine the factors that cause deterioration as well as the extent of damage that necessitates the appropriate repairs and maintenance (Transport Research Laboratory, 2015). To accomplish this objective, visual condition surveys may be conducted as well as invasive tests. Some types of testing allow local authorities to determine the quality and characteristics of pavement layers, while others measure the thickness of pavement and the changes that have taken place over time. In addition, some tests also allow local authorities to obtain samples and test materials used (Transport Research Laboratory, 2015).

Monitoring necessitates an understanding of the pavement life cycle. Monitoring, as a process, begins during the pavement design process, followed by an assessment of pavement performance and life. During the process of monitoring, engineers and other people involved aim to collect data about the quality and condition of pavements. Paving technicians may note the amount of work done and provide hand written records about the state of roads and pavements (Transport Research Laboratory, 2015). Throughout the assessment process, local authorities must focus on extending the life span of pavements. Local authorities may use existing records or data to compare the life span of pavements over the years. With new technologies and the application of novel systems or procedures, local authorities may seek to extend the life span of pavements by focusing on establishing resiliency. Strategic planning may include the identification of faulty or damaged pavements and conducting research to determine resilient and durable materials as well as effective operations and practices (Transport Research Laboratory, 2015).

When it comes to pavement management, obtaining an image or illustration of the road network is highly important. The illustration shows the lengths of different roads in the road network. Using the illustration or representation, management officials would be able to locate important information that shows the outcomes of surveys and other visual data collected, as well as an inventory of the details of the construction process and dimensions (UK Roads Liaison Group, 2011). Visual imagery of road networks may be collated through a visual condition survey. Local authorities may commission third parties to conduct the survey. Organisations such as the Transport Research

Laboratory (TRL), for instance, offer various services including the Coarse Visual Inspection (CVI) and the Detailed Visual Inspection (DVI). Engineers are responsible for identifying areas in networks that would necessitate repairs and maintenance operations (Transport Research Laboratory, 2015a).

Traditionally, local road authorities have used Coarse Visual Inspections (CVI) to define the condition of the road surface. However, there were some issues with the results across the UK regarding inconsistency and inaccuracy due to the commission of different third parties to conduct the survey (Worcestershire County Council, 2007). In order to standardise the methodology of surveys, DfT announced that authorities should use machine surveys, therefore, in 2005, SCANNER (Surface Condition Assessment for the National Network of Roads) was presented to produce the Road Condition Indicators (RCI) for A, B and C classified roads (Worcestershire County Council, 2007).

Obtaining imagery or illustrations is highly important during the inspection and monitoring to make the process more doable for personnel. On-site inspection may be the most effective means of surveying or inspecting but the length of road networks throughout local communities necessitates a more timely and efficient approach. By using new technologies, local authorities may conduct inspections by relying on real time imaging and representation of roads. In this way, it becomes easier for local authorities to identify problem and target areas, and consequently implement measures to repair damaged pavements (Transport Research Laboratory, 2015).

A separate procedure is followed when inspecting airfield pavements. In airfield pavements, Maintenance Management Organisations (MMO) are in charge of inspecting sites on a regular basis. In addition, specialist airfield pavement engineers work together to identify problem areas and implement solutions (Defence Infrastructure Organisation, 2011). Airfield Pavement Management is a collaborative effort between the Prime Contractor or MMO and the Defence Infrastructure Organisation Professional and Technical Services. Under the Prime Contractor or MMO, the schedule of annual maintenance is determined. Hence, monthly inspections, updates, and reports are conducted by MMOs. Under the Defence Infrastructure Organisation, personnel look into maintenance operations and determine whether these meet life extension requirements. Furthermore, the organisation is also in charge of putting together the Airfield Maintenance Inspection Report (Defence Infrastructure Organisation, 2011).

Pavement inspection and monitoring must be an ongoing action or process. Local authorities should conduct regular inspections and monitoring, as these actions are essential in the preservation of pavements, as well as in an effort to reduce spending or budget allocation of pavement maintenance. Pavement inspection and monitoring give way to the early detection of existing and potential problems. As a result, local authorities may immediately implement measures or actions when potential or existing damage is detected. In this way, local authorities are able to avoid added cost on spending for pavement maintenance.

2.3.3 Pavement Maintenance

Pavement maintenance practices are common standard among various councils or local authorities throughout the UK. Local councils are in charge of overseeing the maintenance of highways, including footpaths and pavements. Common problems that necessitate pavement maintenance include potholes on pavement, as well as other road or highway related problems such as damaged traffic lights or street lighting, need for street cleaning, and damaged or missing nameplates in streets (Coventry City Council, 2015; Bristol City Council, 2015). Other problems that may require local road agencies' attention include dislodged or damaged pavements and kerbs, damaged or unavailable access ramps, and proper construction of pavements, particularly in areas that are linked to private properties (Bristol City Council, 2015). When conducting pavement maintenance, local authorities consider the size of the damage, type of problem, and the risk that the damage or problem may affect the public (Thurrock City Council, 2015).

Pavement maintenance is a continuous activity because of the deterioration with time. In addition, the policy framework continues to develop because of increasing traffic volumes, developments in materials and techniques available to engineers, and climate change. For this reason, the maintenance codes will be subject to periodic reviews to ensure that authorities have access to best practices across the range of pavement maintenance activities (Department for Transport, 2005).

The main aim of pavement maintenance is to keep the road network maintained for the movement of people and vehicles safely. However, asset management, continuous improvement, corporate policy and integrated transport should be taken into account when considering the core objectives, such as delivering a safe, serviceable and sustainable network as summarised below (UK Roads Liaison Group, 2005):

- Road Network Safety: Meeting the needs of road users for safety and complying with statutory obligations;
- Road Network Serviceability: Achieving integrity, enhancing condition and maintaining reliability;
- Road Network Sustainability: Minimising cost over time, maximising environmental contribution and maximising value to the community.

UK Roads Liaison Group (2005) defined pavement maintenance as a wide ranging function, including the following main activities:

- Reactive Maintenance: repairs following emergencies, reports of inspections and complaints;

- Routine Maintenance: repairs according to a regular schedule, such as patching, cleaning and maintaining pavements;

- Programmed Maintenance: maintaining road network schemes according to a planned schedule;

- Regulatory Maintenance: in England, under the statutory duty for road network management, traffic managers should inspect and regulate the activities of others;

- Winter Service: clearing snow and ice and salting roads;

- Weather and Other Emergencies: responding to a planned emergency.

One of the first steps of pavement maintenance is assessment. Huang et al (2014) discussed Life Cycle Assessment (LCA) as part of road pavement maintenance in the UK. In LCA, assessment focuses on the original design, particularly the durability of the materials used during construction. Furthermore, assessment also focuses on how pavement maintenance will affect traffic. Huang et al (2014) conducted a case study of inter-urban roads in the UK to determine the impact of extended LCA in maintenance, particularly when it comes to road emissions. In the research, Huang et al (2014) discussed various aspects of pavement maintenance. Typically, pavement maintenance or intervention and rehabilitation occurs within 20 years. During this time, public agencies involved must create pavement design based on existing resources and trends to ensure the use of durable materials and minimal impact on traffic and the environment (Huang et al., 2014).

Outcomes of the Huang et al (2014) research also show specific considerations in pavement maintenance. Maintenance works in road networks may lead to significant disruption in traffic. Furthermore, they could lead to emissions that pose risks to the environment. For these reasons, the researchers recommended the need for micro-simulation of traffic flows prior to conducting road maintenance works. In this way, traffic disruptions may be prevented or addressed as they occur, thereby similarly reducing emissions (Huang et al., 2014).

The Roads Liaison Group manages the UK Roads Board, the UK Bridges Board, the UK Lighting Board, and the UK Traffic Management Board. The UK Roads Board is in charge of overseeing the SCANNER Project Management Group, the UKPMS Steering Group, the Footway and Cycle-tracks Management Group, and the Roads Performance Management Group (UK Roads Liaison Group, 2005).

2.4 Pavement Maintenance Practice within UK Local Road Authorities

Pavement maintenance management is distributed among local authorities in the UK. Local authorities throughout the UK fall under various councils: the English County, London Borough, Metropolitan Borough, English District, English Unitary, Welsh Unitary, Scottish Unitary, and Northern Ireland District Councils. Councils are responsible for strategic planning and implementation of projects and initiatives related to transport (Department for Transport, 2006). In local councils, network hierarchy follows the succeeding flow: (1) motorway, (2) strategic route, (3) main distributor, (4) secondary distributor, (5) link road, and (6) local access road (Department for Transport, 2006).

2.4.1 Pavement Condition Assessment

When it comes to the assessment of pavement condition, real time information is highly valued because it allows local authorities to take control of the process of maintenance, as information is readily available when needed. Furthermore, real time information allows local authorities to trace sources of information and redirect concerns to relevant agencies. Customers or people in the community may contribute to asset data systems by providing information. People may contact local customer centres to report damaged pavements as well as road issues that necessitate immediate attention. Aside from real time information, local authorities also need data about the life performance or cycle of pavements. Based on this information, local authorities may determine why and how failures have occurred in the past and will occur in the future. This information is relevant in helping local authorities make informed decisions (Aggregate Industries Ltd., 2015).

Radopoulou and Brilakis (2015) conducted research on the detection of road defects for pavement condition assessment. Based on the outcomes of the research, Radopoulou and Brilakis (2015) asserted that pavement condition assessment is an important aspect of maintenance because it provides information about the current conditions in roads that would necessitate action. Consequently, local authorities would be able to determine the appropriate action for maintenance and management. The results of pavement condition assessments guide local authorities in making informed decisions for pavement maintenance. Considering the important role and function of pavement condition assessment, Radopoulou and Brilakis (2015) recommended the use of new technologies that would help bring about real time information or data for decision-makers. Traditionally, old practices take much time and effort, and are also expensive to perform. New technologies, however, make it easy for local authorities to easily conduct condition assessment in a timely and more efficient manner. Radopoulou and Brilakis (2015) discussed a technology –the Semantic Texton Forests (STF) algorithm – to easily detect patches and potholes as well as three different types of cracks using a camera. The images returned to local authorities will easily reveal the type and severity of damage, which would then help decision makers determine the appropriate maintenance practice or procedure to implement.

Robinson et al. (1998) identified a number of defects that influence the condition of pavement. Defects include pot holes, cracking, longitudinal-profile, transverse-profile, surface friction, etc. These defects are measured by both TRACS (TRAffic-speed Condition Surveys) and SCANNER (Surface Condition Assessment for the National Network of Roads). TRACS surveys are used by the Highway Agency on the trunk road network to measure the surface condition of the trunk roads.

In order to provide a consistent method of assessing the condition of pavement, UK Roads Board developed SCANNER (Surface Condition Assessment for the National Network of Roads) surveys. Automated pavement condition survey machines have been used in this method throughout the UK (UK Roads Board, 2011). Typical SCANNER survey vehicles are shown in Figures 2.1, 2.2 and 2.3 below:

Figure 2.1: Jacobs Laser RST26 vehicle (UK Roads Board, 2011)

Figure 2.2: WDM RAV4 vehicle (UK Roads Board, 2011)

Figure 2.3: Yotta (DCL) Roadware ARAN1 vehicle (UK Roads Board, 2011)

Local authorities use the SCANNER survey to conduct different types of inspections within their networks. Types of inspections that may be conducted using the SCANNER include safety inspections, service inspections, and condition surveys. Outcomes of surveys include different types of information such as road hierarchy, road categories, and survey frequency. Road hierarchies include the identification of road types such as strategic routes, main distributors, secondary distributors, link roads, and local access, which may then be categorised. SCANNER data also provides information about the frequency of surveys conducted, whether monthly or yearly (Department of Transport, 2006).

SCANNER type data plays an important role in local authorities' decision making, particularly when it comes to identifying appropriate and pertinent solutions to existing problems. "Current practice observed during the consultation process was for most authorities to use SCANNER type data, as part of an initial sift of information to identify schemes and then to revert to more tried and tested inspections" (Department of Transport, 2006). Hence, SCANNER type data bears supplemental information that helps local authorities interpret or make sense of existing information gleaned using other types of surveys or inspections (Department of Transport, 2006).

The SCANNER Road Condition Indicator (RCI) has been developed to identify the overall condition of the road. Measured parameters by SCANNER are used to calculate the RCI, which includes (Department for Transport, 2012b):

- Longitudinal-profile: Bumpiness along the road surface which is measured by 3m and 10m.
- Cracking intensity of the road surface
- Average texture depth of the road surface
- Average rut depth along the length of the road

The RCI is the result of the SCANNER survey and it is used to identify the need for road maintenance as it measures the overall condition of each 10 m subsection, where the scores can be divided into three categories (UK Roads Board, 2011):

- Green: road is in good condition
- Amber: road has some deterioration and needs to be investigated for planned maintenance treatment
- Red: road is in poor overall condition which requires planned maintenance soon

2.4.2 Pavement Maintenance Management Systems (PMMS)

Local road authorities developed various systems for pavement maintenance management to control expenditure. Hence, the Department of Transport (DoT) then, Department for Transport (DfT) now, designed a system to manage the routine pavement maintenance of roads in England. The system enabled inventory data of roads to be collected using small computers that were held by hand and then imported into personal computers or mainframes for processing (Phillips, 1994).

In addition, local road authorities assessed the need for non-routine maintenance on the roads across the UK. DoT used a system with two levels, where the first level included coarse assessment by using the High-speed Road Monitor (HRM), which travels at 80 km/hr. The Transport Research Laboratory (TRL) developed the HRM to measure longitudinal-profile and rutting of pavement, where these measurements are recorded automatically and transferred to computers to be analysed (Phillips, 1994).

The second level included detailed assessment using a combination of visual assessment and machine assessment. In order to carry out the machine surveys, the deflectograph was used to measure the transient deflection of pavements under a known wheel load. Visual assessment methods were used to record defects, and the condition of pavement data was analysed to provide recommendations for treatment and a decision making regarding priorities (Phillips, 1994).

Another survey machine was introduced to measure the wet skidding resistance of the road surface; it is called the Sideway-force Coefficient Routine Investigation Machine (SCRIM) which travels at 50 km/hr; it is used for the national road network on a three-year cycle (Phillips, 1994).

Phillips (1994) investigated all the systems and concluded that the data sets which were produced by these systems were not coordinated. Aas the systems were separate, they were related by a common referencing system, but data were not combined. Subsequently, deciding on priorities was difficult, as an engineer would be faced with several survey results for the same section of road, some of which – computerised, and others - in paper form (Phillips, 1994).

Local road authorities faced another problem, as not all the methods were relevant to all classes of road. However, to develop a more efficient system, the Local Authority Associations (LAA) and the DoT considered a new pavement management system (PMS) in the 1980s, now known as the United Kingdom Pavement Management

System (UKPMS) to replace the various existing methods of visual assessment and to manage the maintenance for all roads (Phillips, 1994).

Many local authorities in the UK are using the UKPMS, which is the national standard for a computer system that supports the assessment of local road network conditions, the management of programmed maintenance, and the planning of investment on local roads within the UK (Cartwright, 2005).

The UKPMS is primarily used to guide pavement management practices implemented by local authorities. Gathering data is essential in pavement management within the context of local communities as the analysis of existing data and information would help agencies or groups involved to determine problems and issues, particularly those needs that relate to management and maintenance (UK Roads Liaison Group, 2011).

The UKPMS notes the specifications of pavement maintenance. All entities involved in pavement maintenance management such as contractors and suppliers, among others, are expected to meet the specifications set in the UKPMS (UK Roads Liaison Group, 2011b). Every year, an Annual Health Check is conducted in local authorities. The purpose of this is to ensure that all practices and operations comply with the UKPMS systems, specifications, and requirements. Part of the annual assessment is ensuring that all data is submitted for national reporting and that all practices, operations, and outcomes fall under the established Rules and Parameters (UK Roads Liaison Group, 2011c).

Local authorities utilise the UKPMS inventory to implement management and maintenance practices and operations. The UKPMS inventory functions as follows:

- 'Refine' the Pavement Type associated with a Defect record in a Condition Survey
- Calculate the Defectiveness of the observed Defect and assign a rating value to the said Defect
- Calculate the estimated work costs of the treatments generated by the Treatment Selection process.

(UK Roads Liaison Group, 2011c)

2.4.3 Major Issues Affecting Pavement Maintenance Works

In recent years, one of the factors that has influenced pavement maintenance management in general is environmental sustainability. For this reason, several practices in recent years have raised the need for sustainable pavement maintenance. The National Cooperative Highway Research Program (2011) conducted research into the matter and discovered the following issues and considerations in relation to pavement maintenance:

- Identifying ways to implement and use environmentally sustainable practices or operations and treatment
- Applying life cycle assessment (LCA) and cost analysis methods in pavement preservation and maintenance
- Conducting research to collate information about environmentally sustainable practices in pavement maintenance management to guide practices, as well as training to improve the skills and competencies of personnel
- Conducting research to determine the viability of recycled or alternative materials for maintenance and preservation of pavement
- Conducting research to determine and establish standards (i.e. noise standards) in pavement preservation and maintenance throughout the life cycle
- Conducting research to quantify the frequency and extent of damages on pavements such as the number of cracks to accurately measure the time needed for repairs or maintenance and resources or materials
- Conducting research to influence policy development in pavement maintenance, identify new technologies to use in pavement maintenance and repairs, and establish new specifications, materials, equipment, and standards in relation to environmental sustainability

(National Cooperative Highway Research Program, 2011)

In carrying out pavement maintenance, engineers and managers need to take into consideration various issues when deciding on options and methods of working. Such issues include dealing with existing Statutory Undertakers' buried services, the need for traffic management and traffic diversion, dealing with listed structures etc. The following sections present a review of some of these issues (Ziad, 2009).

2.4.3.1 Statutory Undertakers' Apparatus

Roads do not only carry vehicular and pedestrian traffic, but also there are usually several Statutory Undertakers' pipes and mains buried beneath the road base (Ziad, 2009).

A major issue when carrying out any pavement maintenance therefore is dealing with existing buried services during construction. An initial search and consultation is undertaken with the main Statutory Undertakers to ascertain the presence and location of any of their buried plant or equipment within the sections to be maintained. The following organisations are usually consulted (Ziad, 2009 cited HAUC, 1992):

- British Telecommunications plc;
- National Grid (Transco) for gas mains;
- The local water company (United Utilities Water Services in the North West of England);
- The local electricity distribution company (United Utilities Electricity Services in the North West of England); and
- Other telecommunication and cable companies known in the area such as NTL (Virgin Media).

Following the initial consultation, a detailed search is required to verify the accuracy of the details, check on any other services present and measure the actual positions and depths of each service before a detailed design of road works commences. The extent of any service alterations is dependent on the nature and scope of the proposed road works (Ziad, 2009 cited HAUC, 1992).

Any necessary service diversions or alterations are carried out by the relevant Statutory Undertakers or their agents, and the diversion can sometimes be completed prior to the main road works contract or programmed as part of the main construction duration to minimise traffic and other disruptions in the area (Ziad, 2009 cited HAUC, 1992).

The approved document that governs the required actions where major road works or major transport works affect Statutory Undertakers' apparatus, is the Code of Practice: Measures Necessary where Apparatus is Affected by Major Works (Diversionary

Works), published by the Highway Authorities & Utilities Committee (HAUC), under the auspices of the New Roads and Street Works Act 1991 (Ziad, 2009 cited HAUC, 1992).

The cost of diverting Statutory Undertakers' plant is a major issue, as under the New Roads and Street Work Act 1991 (NRASWA) cost-sharing principles, the highway authority must carry 82% of the total cost of the diversion while the Statutory Undertaker bears 18% of such costs (Ziad, 2009 cited HAUC, 1992).

The cost of service diversion or alteration can be extremely high, and the ultimate design will carefully consider the need for actual diversion, and whether it would be feasible and acceptable by the relevant Statutory Undertaker to support services under consideration in place and protect them for the duration of the road work instead of the more costly diversion option (Ziad, 2009).

2.4.3.2 Traffic Management

Carrying out pavement maintenance work can potentially cause a severe hindrance to existing traffic as well as to the normal life of the local community. Where the work is likely to involve full or partial road closures to facilitate the safe completion of the road works, this will cause disruption and possible traffic congestion affecting local residents, traders, through traffic, pedestrians and cyclists. This can be extremely costly in terms of lost time to motorists, noise and dust on diversion routes as well as safety and environmental considerations (Ziad, 2009).

The impact of road works on traffic is therefore a major concern and needs careful planning and close coordination with many agencies, such as the Police and emergency services. The local authority coordinates all work carried out on the road, and notifies all agencies and organisations concerned of any planned work on the road or such involving traffic management and diversion in particular, well in advance (Ziad, 2009).

Traffic management issues, the need for traffic diversion and the availability of suitable diversion routes are most important considerations in the selection of options and methods of undertaking road works (Ziad, 2009).

2.4.3.3 Dealing with Listed Structures

Buildings and structures are listed in order to protect the best of the country's built heritage. Currently the listing in England and Wales comes under the Planning (Listed Buildings and Conservation Areas) Act 1990 which puts a statutory duty on the Secretary of State to compile a list of buildings of special architectural or historic interest (Ziad, 2009 cited Craven District Council, 2007).

Buildings and structures that are listed are subject to a much greater degree of control in respect of alteration and demolition than other structures. A building that has been listed will not be demolished, extended or altered if there is no permission from the local planning authority, because even what may appear as minor alterations to a listed building or structure could alter its character and as such, a 'Listed Building Consent' would be required (Ziad, 2009 cited Craven District Council, 2007).

For pavement maintenance schemes involving listed structures, it is therefore vital to start early consultation with the local planning authority to determine the need for a Listed Building Consent, and if required, comply with any conditions imposed by such consent to allow the proposed road works to proceed in a timely manner.

2.5 Issues with Allocated Budget

The national government is in charge of monitoring the performance and progress of local authorities. Since local authorities are in charge of maintaining road networks, the quality and progress of work must meet the standards set by the national government (UK Roads Liaison Group, 2011a).

A limited budget is one factor that affects pavement maintenance among local authorities. In Surrey, the local government only has a £2 million budget for pavement maintenance for the years 2015 to 2016. As a result, the local government needs to prioritise maintenance projects. With such limited budget, local authorities can only work on selected pavement maintenance projects. In addition, other backlog projects also require immediate attention. Hence, the quality of pavements as well as the frequency of repairs and maintenance largely depend on the existing budget for local authorities (Surrey County Council, 2015).

In June 2015, a document was leaked outlining the road repairs and maintenance that were put on hold as a result of budget cuts (Smith, 2015). Transport NI was assigned to the road network that necessitated repairs. Problems arose when a budget cut was implemented for Transport NI's road maintenance and repairs. From £40 million, Transport NI's budget was reduced to £12.8 million. The said budget cut resulted in the reduction of repairs and maintenance projects in motorway bridges. If damage makes these bridges unpassable, then they will simply be closed since there is no allocated budget for the repairs (Smith, 2015).

Bradbury et al. (2012) conducted research to determine the impact of budget cuts on road maintenance throughout Scotland. The researchers conducted quantitative analysis in the research to measure the economic, environmental, and social impact of specific maintenance budget schemes. The outcomes of the research prove that limited budget leads to a decline in the quality of life of people considering weaker links in their road networks. Travel becomes more difficult and mobility is limited. This is particularly true in remote communities that are separated from busy urban communities. Furthermore, a reduction in budget for pavement maintenance shows that it will lead to greater costs in the future. If the government limits the existing budget for pavement maintenance, then local road authorities would be forced to select only a few maintenance projects or low cost materials that are of poor quality. In the long run, this will lead to higher costs due to the greater damage that must be addressed (Bradbury et al., 2012).

2.6 Limitations and Shortcomings in Existing Pavement Maintenance Management Practices in Local Authorities

Based on the literature review of the existing pavement maintenance management practices within the UK local road authorities, it is clear that there are two levels with regard to the level of implementation of the accepted pavement maintenance management principles. The two levels are based on the pavement maintenance management philosophy which has for some years now been promoted in the UK by the Well-maintained Highways: Code of Practice for Highway maintenance Management, which is recognised within the local road authorities as being the established standard for pavement maintenance management.

Firstly, many local road authorities have adopted the SCANNER surveys with regard to the road condition surveys, as it is recommended in the code. Although SCANNER is a practical, time saving method of collecting condition data and produces Best Value Performance Indicators (BVPIs) for comparison between local road authorities, it is not as accurate as expected, as it can record road markings such as cracks in the road surface but only scans a 3.2m width of the road. However, a visual survey is needed as well as SCANNER surveys to obtain comprehensive data. In addition, the SCANNER technology needs development to overcome the shortcoming of its accuracy.

Secondly, regarding the use of formal computerised Pavement Maintenance Management Systems (PMMSs) promoted by the Code of Practice for Highway Maintenance Management, although the existing pavement management system (UKPMS) provides comprehensive databases and supports decision making in prioritising maintenance works, a number of issues with performance have been identified. Issues identified with UKPMS include:

- Inaccuracy of the input survey data leading to unreliability of the processed data by UKPMS,
- Network referencing is identified as a list of sections, which causes inaccuracy of position referencing,
- Data processing time through UKPMS is very slow, while the input data from SCANNER is very large,
- Prioritising maintenance based on condition or econometric principles, where other factors are not taken into account.

Despite the existence of pavement management and maintenance systems in the UK, local road authorities need to adopt a joint strategy to develop these systems. However, considering a Geographical Information System (GIS) based PMMS could be a practical solution to overcome the shortcomings in the existing systems. In addition to GIS capability of dealing with spatial data, storing, analysing and visualising results on maps, considering more factors that influence pavement maintenance prioritisation is essential for an effective PMMS.

2.7 Summary of Chapter Two

This chapter explores pavement maintenance management in the UK. Various aspects of pavement maintenance management were investigated, including pavement maintenance in general, the existing pavement date records in the UK, pavement inspection and monitoring practices, and pavement maintenance. Other topics explored in the research include pavement maintenance management practices among local road authorities within the UK, particularly their pavement condition assessment, pavement maintenance management systems, major issues affecting pavement maintenance management among local authorities, and limitations and shortcomings in the existing pavement maintenance management practices in local authorities. The role and function of SCANNER and UKPMS were also explored.

Based on the outcomes of the literature review, pavement maintenance management refers to various practices that help improve pavement surfaces to avoid accidents and risks to safety as well as traffic and experiences on the road. Pavement maintenance may be corrective or conducted for emergency purposes. Nevertheless, the most important action during pavement maintenance is prevention. Preventive measures help local road authorities assess road conditions and make plans to increase the life span of pavement and, thereby, reduce spending on pavement maintenance as well as disruptions to traffic. For this reason, local road authorities must prioritise prevention as an aspect of pavement maintenance management.

The review of related literature sheds light on an important issue that affect pavement maintenance, which is budget cuts. Austerity limits the capacity of local road authorities to meet the needs for maintenance and prevention. Many local authorities have reported massive backlogs in projects due to lack of budget. In addition to this is the increasing need for pavement maintenance and road repairs. Budget cuts affect the prioritisation of pavement maintenance, which means that measures must be taken by the government and local authorities to prevent the impending impact of budget cuts.

Some solutions or recommendations that were briefly raised in the chapter include implementing sustainable policies and preventive measures to help address problems in relation to budget. Refocusing efforts on extending the life cycle of pavements will reduce spending on pavement maintenance and repairs. Overall, local road authorities need to adopt a joint strategy to develop systems for pavement maintenance management, while remaining within existing budget allocations. Considering GIS based PMMS including the most effective factors of pavement maintenance prioritisation could be a practical solution to overcoming the shortcomings in the existing systems. However, the government also needs to look for ways to increase budget allocations for roads and pavement maintenance as the quality of pavement significantly affects the quality of transportation, as well as the nature of traffic along all road networks.

Chapter Three

Best Practice Methods of Pavement Maintenance Management Using GIS

3.1 Introduction

In carrying out pavement maintenance, many factors other than road condition have to be taken into account before issuing a priority list for implementation of road works and giving its deserved priority rank. Such important factors include, for example, the importance of the road, the Annual Average Daily Traffic (AADT), available budget, road class, safety issues, etc.

However, because of the limited annual fund available for maintenance of roads, decisions have to be made to implement schemes that provide the highest value of return to the road network in general.

This chapter provides a comprehensive literature review on the role of GIS in PMMS and the suitability of GIS in this research. The chapter then presents other applications and tools involved in decision making.

3.2 Geographical Information Systems (GIS)

3.2.1 Definition of GIS

Heywood et al (2011) compared the definitions of Geographical Information Systems (GIS) from several authors and concluded that the definitions cover the following main components:

- GIS is a computer system;
- GIS uses spatially referenced data; and
- GIS carries out various data analysis tasks.

Heywood et al (2011) also argued that there is as much debate about the components of GIS as there is about its definition. However, a GIS needs an application area to operate, which has its own ideas and procedures (Heywood et al., 2011).

Burrough (1986) provided one of the most widely quoted definitions of GIS as "a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes".

Alternatively, Kennedy (2009) stated that it is impossible to give a short, meaningful description of GIS, as it depends on different points of view. However, he provided a generic definition of GIS for starters as "an organised collection of computer hardware and software, people, money, and organisational infrastructure that makes possible the acquisition and storage of geographic and related attribute data, for purposes of retrieval, analysis, synthesis, and display to promote understanding and assist decision making".

3.2.2 History of GIS

Gray (2006) quoted Tufte (1983), who stated that the development of GIS goes back to 1855, when John Snow discovered the source of the cholera epidemic in London by creating a dot map. As a result, the use of geographic visualisation in areas attracted attention after this discovery (Tufte, 1983). Figure 3.1 shows a dot map.

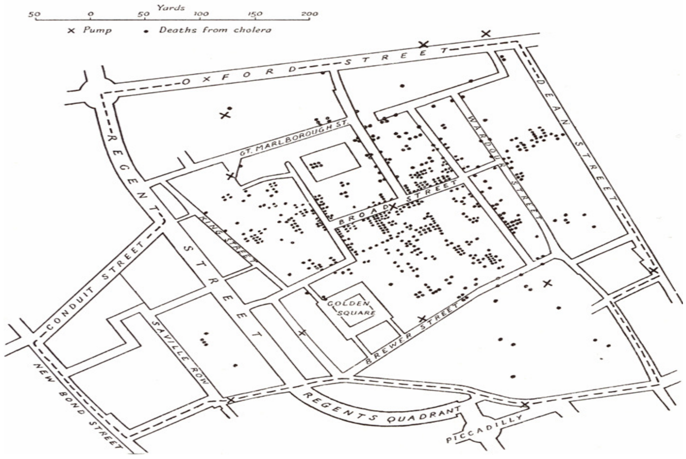


Figure 3.1: Cholera Epidemic Dot Map (Gray, 2006 after Tufte, 1983)

However, the starting point of computer-based GIS, according to Coppock and Rhind (1991), goes back to the mid-1960s. In 1964, the Federal Department of Energy, Mines, and Resources in Ontario developed the first operational GIS. Roger Tomlinson, who became known as the "father of GIS", called it "Canadian Geographic Information System" (CGIS). CGIS was used to store, analyse, and manipulate data.

GIS packages were offered to public and private organisations in the 1970s and the Environmental Systems Research Institute (ESRI) was the leading seller of GIS software. ESRI released the ArcInfo package in 1981, and since then, several updated GIS packages have been released by ESRI (ESRI, 2012).

3.3 GIS in Pavement Maintenance

Pavement Maintenance Management Systems (PMMSs) with spatial application capabilities are employed as decision support mechanisms in the protection and management of investment (Flintsch & Chen, 2007). That is, PMMSs are developed at a local level to enhance the process of decision-making – more specifically, to gain an insight into the implications of decisions, and limit adverse impacts and maintenance costs. The fact that the PMMS incorporates technology is considered essential for promoting and enhancing decision-making (Abo-Hashema et al., 2006).

Nevertheless, pavement maintenance is not an exact science. It is expected that two different road segments of the same type do not have the same repair methods. Each road segment location requires good judgement by experienced personnel (Haas et al., 1994). Keeping road condition to an acceptable level entails routine maintenance work in the form of removing surface corrugation, patching, filling ruts, pouring cracks, bleeding surfaces, among others. Rehabilitation, overlays, and resurfacing are considered major maintenance activities (AASHTO, 1993).

Aging roads are more vulnerable to natural disasters, which often disrupt the service provided by these road networks (Housner and Thiel, 1995). Road maintenance entwines utility works, also making it difficult to independently address road network maintenance activities. Installations on new utility lines interrupt road maintenance schedules, especially in regions where the mere size of the network and number of roads constrain maintenance and repair programmes. This is one reason why the broadening GIS applications are more extensively integrated into PMMS (Rhind, 1989).

3.3.1 Dynamic Segmentation

This tool facilitates the decision making process for RMMS. Attributes are dynamically segmented to create a graphical representation of GIS (results shown in Figure 3.2).

The dynamic segmentation technique has the capability to translate a linear feature into segments, which would mean to link several sets of attributes to any given road segment and create a graphical representation for the user to visualise. Dynamic segmentation is developed by GIS analysts. It allows for interactive query on output elements that is quick and easy to use. The application capabilities save time and effort, provide structure and overlapping data on one street, use accurate methods to calculate road maintenance regions and volumes, and prioritise the need for road segments (Williams and Schuman, 1995).

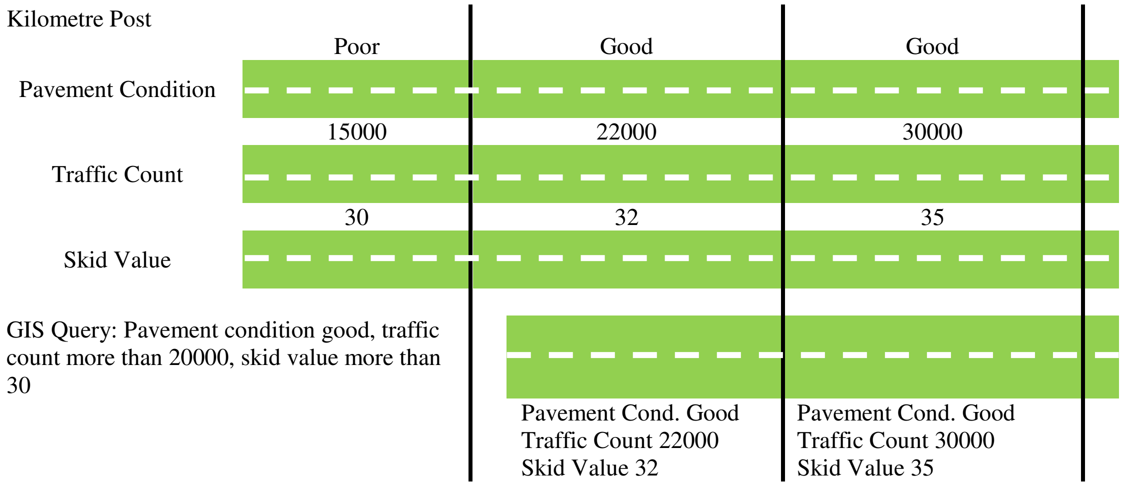


Figure 3.2: Illustration of Dynamic Segmentation (Al-Swailmi and Al-Mulhem, 1998)

3.3.2 Spatial Analysis Applications for Pavement Management

Spatial analysis technologies are useful alternative tools for PMMS because pavement and asset management systems are supported with the compilation of a tremendous amount of information, available in a wide array of referencing systems, formats, and media (Flintsch and Chen, 2007). The application assists in the analysis of several planning and operational problems on pavement management that include scale, time, and format, whereas the measurement, mapping, monitoring, and modelling of spatial phenomena are enhanced (Miles and Ho, 1999). This technology has the capability to efficiently integrate, store, and query spatially referenced data to support many pertinent decision processes.

Goodchild & Longley (1999) define these as a collection of methods that are effective spatial data. These combine manipulations, transformations and other techniques that show the less obvious patterns and anomalies that could enhance and support decisions on road pavement prioritisation. These data form geographical features referenced by positions and attributes in analogue or readable digital formats (OMB, 2010). Spatial analysis lets a user query, map, create, and analyse cell-based raster data, and conduct comprehensive raster or vector analysis. As a result, the user can confidently derive new information from existing data and question information across multiple data layers. Fully integrated cell-based raster data using traditional vector data sources is also made possible.

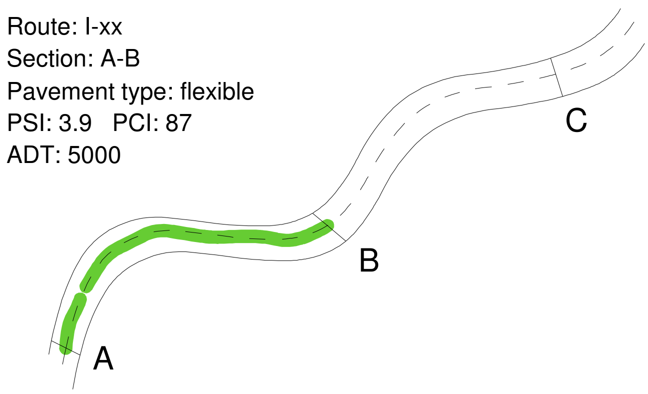


Figure 3.3: Spatial Application Function Scheme (Flintsch & Chen, 2007)

Spatial applications generate a simplistic view of a complex system. The technology relies on the branch of geometrical mathematics, topology, which concerns spatial relationships that correlate spatial entities. Topology is about the connectedness, adjacency, enclosure, and other geometric properties of objects (NHI, 1997). Figure 3.3 presents the spatial information on the roadway with tabular or attribute information on pavement structure, condition, and age.

Applications in this dimension facilitate data integration which could be traffic and Maintenance and Rehabilitation (M&R) history or inventory, data collection which includes the processing of gap detection among others, and output presentation such as the average pavement condition. Its functions are extensive so that even weather information could be used to develop pavement performance models, or apply land use policy and traffic predictions into regional development models (Flintsch et al., 2004).

A spatial tool is designed to support the capture, manipulation, analysis, modelling, and display of spatially-referenced data through a system of computer hardware, software, personnel, organisations, and business processes. It is principally applied for solving comprehensive management and planning problems (Lewis & Sutton, 1993).

The appropriate selection of spatial tools, developing the right base map, and correlating these attributes in spatial and cartographic information is a crucial concern in the development and implementation of spatially supported Pavement Maintenance Management Systems (PMMS) tools (AASHTO, 2001).

3.3.3 Gaza PMMS

Pavement Maintenance Management Systems (PMMS) for the city of Gaza are prioritised after the overall condition of network sections is defined, and each segment treatment is determined with its equivalent cost (Jendia & Al Hallaq, 2005). In choosing, a logical order is established by the ranking index formula that is a combination of section condition, traffic exposure and functional classification (Ali & Al-Qatabi, 1995). A decision made on prioritisation is followed with a budget formulation document, more particularly for clarity.

This equation is the basis for the prioritisation on PMMS for road pavements in Gaza.

$$\mathrm{PI} = \frac{1}{PCI} x\ TF\ x\ FC\ x\ MF\ x\ SR$$

Where:

PI = Priority Index.

TF = Traffic Exposure Factor.

FC = Road Classification Factor.

MF = Maintenance History Factor.

SR = Special Factor to emphasise Priority of Specially Designated Routes.

The application requires an orderly process which begins with a proper inventory of the Gaza road network comprising management segments. Each pavement segment condition is examined and a valuation of the condition is performed using a specific criterion. The treatment strategy and cost implications are then defined on each pavement section. Prioritisation is done and is concluded by documenting report results (WSDT, 1994).

The city road network has an existing street coding on roads and built structures that are classified into these categories:

1. Major roads which transverse through the entire city and hold numbers taking the Identification, or ID, form or X00 where X is between 1 and 9.
2. Main roads are of considerable lengths and widths with assigned ID form or XX0.
3. Local access roads have small lengths and widths, numbered in the ID form of XXX. Omar Al-Mukhtar and Al Rasheed Streets are set as reference roads. The first stretches longitudinally from west to east, and has road ID 200. The second is transversely parallel to the sea shore from north to south with road ID 100 (Jendia & Al Hallaq, 2005).

   Figure 3.4 illustrates the Gaza PMMS prioritisation process.

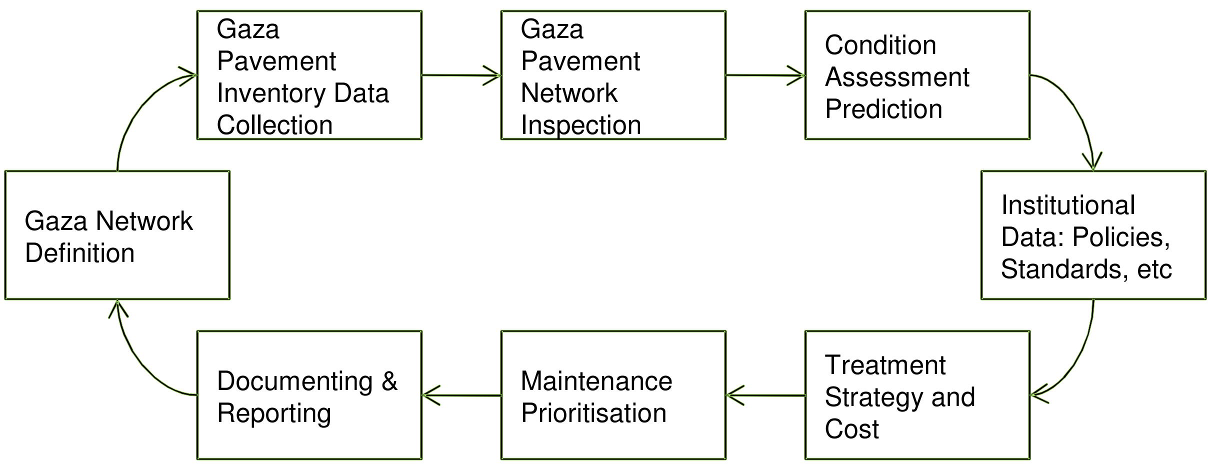


Figure 3.4: Gaza PMMS Process for Road Pavement Prioritisation (Jendia & Al Hallaq, 2005)

Network data collection is conducted once these pavements are in manageable sections. Inventory requires detailed information on pavement condition, traffic, cost and funding. It should include a description of the physical features. Institutional data is also essential in the prioritisation equation. This outlines administration goals, policies, standards, resources, budget details and annual constraints (Ali & Al-Qatabi, 1995).

It is thought that over the long run, the Gaza PMMS database will preserve a large amount of historical pavement condition information which can be used to develop pavement performance curves or models, useful in the prediction of pavement performance (Jendia & Al Hallaq, 2005).

3.3.4 PMMS Model in Al Ain City

A PMMS application in Al Ain has been developed in response to the rapid expansion of road networks in the emirate of Abu Dhabi over the last two decades, which necessitates the protection of these investments. The road network includes over 600 kilometres of centreline dual carriageway paved main roads and 3,000 kilometres of single carriageway paved secondary roads (Abo-Hashema et al., 2006).

Pavement management is supported by spatial technology capabilities to facilitate the archiving of maintenance activities, facilitating various activities onsite and follow-up, and as a decision prioritisation tool. The criticality of PMMS relates to the fact that the life cycle cost on newly built roads is three to seven times more than the expense of preventive maintenance. Thus keeping the road pavement condition at an acceptable level is a priority (Abo-Hashema et al., 2006). The Al Ain PMMS Model supports and enhances a number of activities (Abo-Hashema et al., 2006):

1. Interactive and batch data entry and update;
2. Querying, reporting, and spatial displaying;
3. Thematic representation of information;
4. Maintenance decision support; and
5. Road maintenance needs and analysis.

The framework crafted particularly in this tool places PMMS as a segment of the Pavement Management System (PMS) programme, as an overlay that does not replace

PMS. Figure 3.5 illustrates the overlay concept which correlates PMMS and PMS (Abo-Hashema & Sharaf, 2000; Abo-Hashema et al., 2006; Pinard, 1987).

Pavement Maintenance Management System (PMMS)
Versus Pavement Management System (PMS)

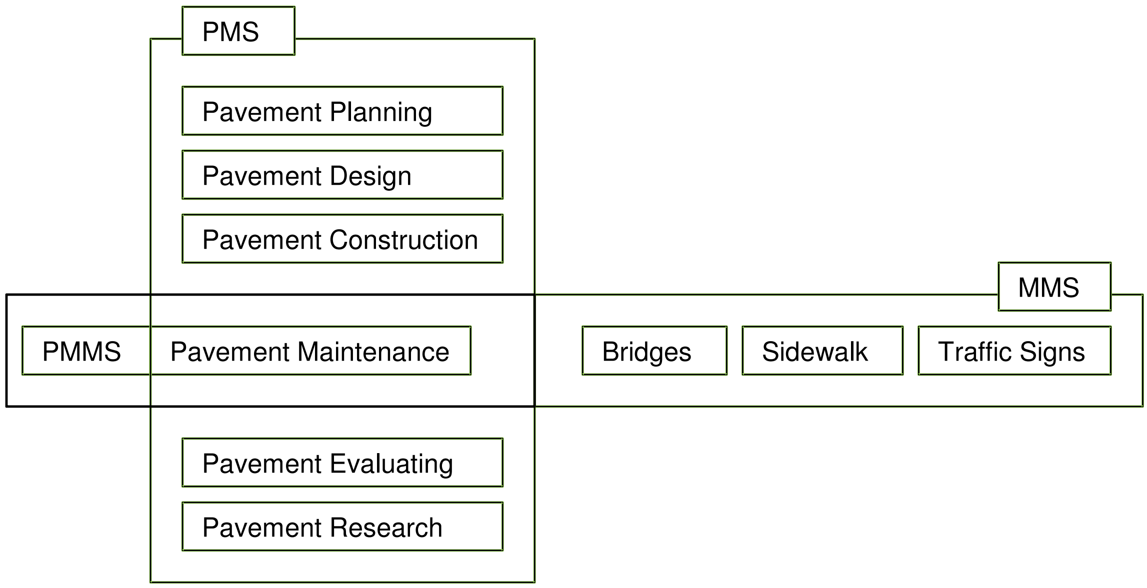


Figure 3.5: Abo-Hashema et al. (2006)

Concurrently, the Al Ain Model defines a fully integrated PMMS and GIS, which allows a liberal interface of data. There are three methods of referencing pavement sections: route milepost, node link, and branch section. The main roads use an identification system based on the node-link method. This means that nodes define key points and the sections between these nodes in each direction are defined as the links. Typically, nodes define intersections, boundaries, and changes in the pavement quality such as surface type. A pavement section comprises three traffic lanes extending 50 metres away from a node. A section is split into sample units of 100 metres length for each traffic lane (Abo-Hashema & Sharaf, 2004).

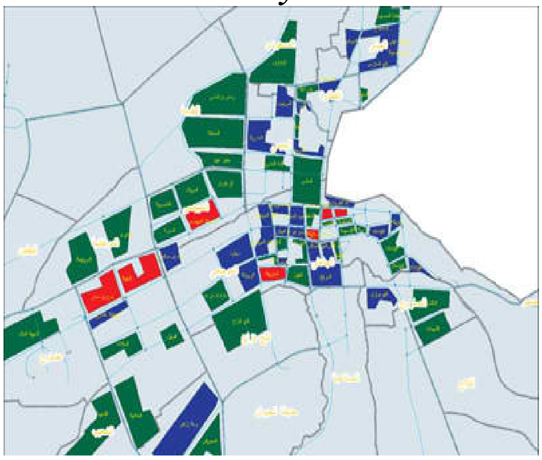
Section inventory is performed, which is followed by a comprehensive distress survey using the Pavement Performance Prediction Modelling (PAVER) model Pavement Condition Index (PCI) values, and a distress map is generated. A distress map is very useful because it provides a complete picture of the locations of pavement surface distress and confirms inspection on these nodes (Pinard, 1987).

A pavement segment is examined for materials failing using a cut out sample layer. The process validates the recommended maintenance treatment determined earlier, and entails laboratory materials testing on in-situ density, sieve analysis, moisture density relation, and the equivalent plasticity index and California bearing ratio. Lab tests are performed after the visual inspection survey is completed (Abo-Hashema et al., 2006).

An important feature of the Al Ain PMMS programme is the agility between the network condition and maintenance needs. Decision priority setting uses a simple worst first rule over all candidate pavement sections.

Figures 3.6a and 3.6b show distress maps for main and secondary roads. Black indicates the first stage, dark grey is used for the second stage, and grey indicates the third stage. Network identification begins the sequence of activities, which is followed by data collection procedures which come through two levels of study: network and project levels. The network level study determines a maintenance plan for main and secondary roads. On a project level, the application generates a final list of projects with detailed scope-of-work for independent projects. Decision prioritisation is enhanced with excellent displaying and querying, materials investigation or road geometric assessment results. These maintenance decisions are archived, and distress maps and all relevant spatial applications are stored for future use.

The work of Abo-Hashema et al (2006) is interesting, with its suggestion that human decision is above science. Insofar as the PMMS framework applies a logical approach to supporting decision prioritisation, at the end a subjective sentiment reigns. This is particularly real in regions where there exists a strong sense of traditionalism and religious focus, and decision prioritisation does not depend entirely on the severity of pavement deterioration given the implied importance of certain roads to the people.

Maintenance Programme Stages for Main Roads	***Maintenance Stages for Secondary Roads***
	
Figure 3.6a Abo-Hashema et al (2006)	Figure 3.6b Abo-Hashema et al (2006)

3.3.5 GIS Application on PMMS in Jeddah Municipality

As the first National GIS Symposium in Saudi Arabia was held in 2005, the GIS technology in the Jeddah municipality is a benchmark in road pavement PMMS for on screen visual data capture for performance analysis and proper visualisation, ground survey, model creation, generation of maps, and for the identification of M&R using unique numbers. The tool effectively supports the supervising engineers, inspectors and department managers in the dimensions of data visualization, data analysis for the purpose of M&R decisions, financial control, asset management and generation of maps (Mansour, 2005).

To begin with, road pavement sections are grouped in small units outlining polygons and combined to complete a pavement branch, which is a road from its start to end. Each district forms a network and when placed all together make the city, archived on the pavement management system (Mansour, 2005).

The work in the Jeddah municipality integrates the micro paver database otherwise known as the access database, and the spatial database or Geomedia warehouse. In doing so, the user can visualise graphically the data for thematic mapping on the road pavement section PMMS (Mansour, 2005).

Figure 3.7 shows the section distress where the micro paver software computes for the pavement condition index PCI on every section, and the deterioration curve is plot. When the maintenance of pavement is done on time, pavement condition is kept between satisfactory and good, which will affect the cost for rehabilitation and keep it to the minimum. However, if the maintenance of pavement is ignored or delayed, pavement condition drops to a very poor state, which will increase the cost dramatically. The application supports the determining of decision prioritisation on the pavement proper time for maintenance.

Pavement Condition Index (PCI)

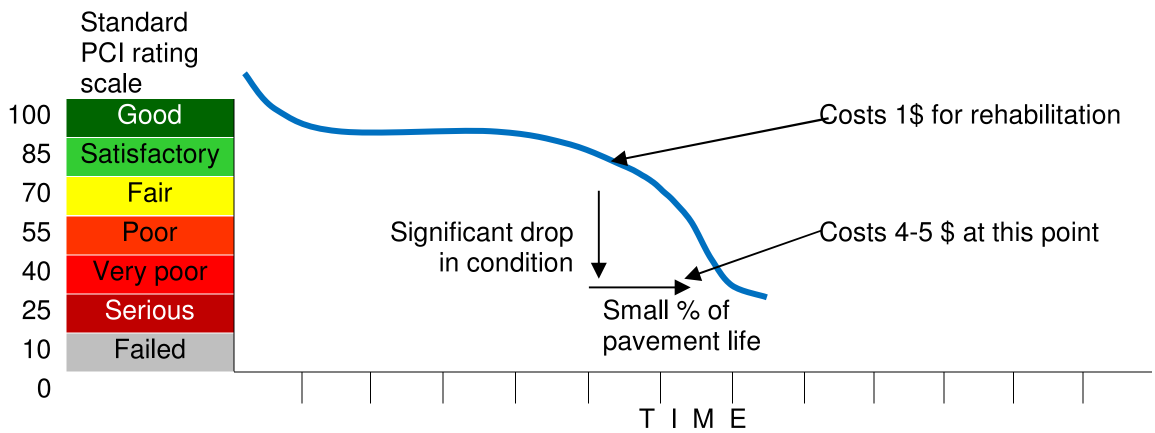


Figure 3.7: Mansour (2005)

The base files used for the GIS application work their way from digital maps prepared by the German Hansa Luftbuild in 1984 in scale 1:10,000 each covering an area of 10 km X 7.5 km, coordinate and projection systems Ein Alabd 1970 and Universal Transverse Mercator or UTM. Centrelines were drawn on all express roads, arterial roads, collective roads and main roads. Roads were broken down into smaller units to enable a capture of precise descriptions. Nodes are located on road intersections and given a node number with correlated traffic lights, signs and significant information (Mansour, 2005).

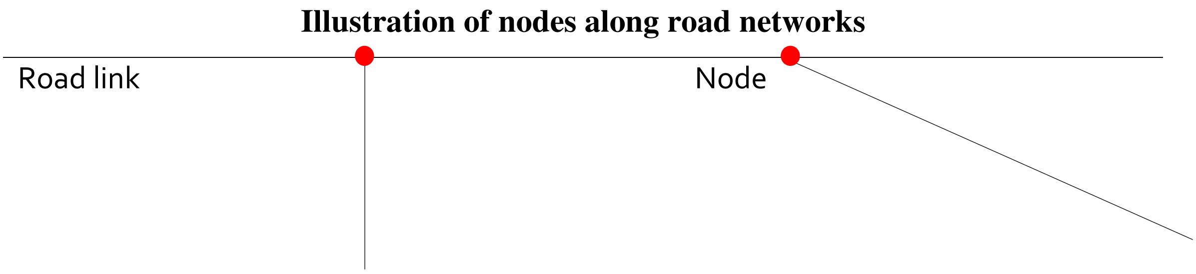


Figure 3.8: Mansour (2005)

3.3.6 ILLINOIS GIS-Based PMS System (ILLIPIMS)

ILLIPIMS is an application developed out of a base map using ESRI's ARC/INFO® in ESRI's and is advanced with the ArcView® GIS 3.2. The modification adopts the data in an earlier tool, the Illinois Pavement Information and Management System (ILLINET), and enhanced with the capabilities of GIS to include non-Interstate pavements (Bham et al., 2001).

ILLIPIMS is unique for its on screen, sequential spatial information particularly useful in reporting, analysing, modifying, predicting and displaying pavement and traffic information for the complete Interstate system of Illinois. Details include type of pavement rehabilitation, traffic information and pavement condition. Any selected section of the interstate map can be plotted to reflect the historical trend of information. Visuals are represented in graphical display either in a map, a graph, or a chart; with colour-coded dynamic legends that make information more understandable by the user (Bham et al., 2001).

3.3.7 Spain PMS

This GIS application of Pavement Management System was developed for Spain's Ministry of Public Works in 2008. It uses the capabilities of GIS to facilitate the generation of the present condition of road pavements, and taking into account the predictive models of behaviour on pavements, proposal development is made possible along with the selection of solutions. The primary design of the system comprises data sets which measure different periods on the road network. The capture of spatial data is stored in geometric inventory; data measured in the form of auscultations is collected in a relational database. These data that are sectioned in modules are analysed through simulations of models of evolution and sets of ad hoc developments. It is a relatively unique concept compatible with new geometric inventories or modifications at the moment in use (Frias & Chaparro, 2008).

This application combines analytical formulae with geographical information which is utilised for presenting results which are the building blocks for forecast and optimisation models, using advanced technologies called 'dynamic segments' (Frias & Chaparro, 2008).

Models of evolution and prediction of the behaviour of the pavements are used in the levels of network for the selection of strategies of maintenance; on project level, in designing pavements, analysis of the cost of the service life of the pavements, or in selecting the optimal affordable design and scheduling of maintenance works. Planning models support the evaluation of strategies or maintenance approaches for the set of pavement network, and the prioritisation of projects with precise maintenance works (Frias & Chaparro, 2008).

Figure 3.9 presents the resulting data of the auscultation of the road network. Those sections of the network where rehabilitation activities have been carried out are indicated, the processed information of this diverse model is generated from the data mentioned earlier.

Indicators, parameters, characteristics and maintenance works

Denomination	Type	Description
IRI	Indicator	Index of Structural Regularity. Related to the security and the comfort.
CRT	Indicator	Coefficient of Cross-sectional Friction. It is an indicator of the state of the adhesion between the tire and the pavements, that is to say, of the security.
Deflections	Indicator	Measure the elastic deformation of a pavement to the passage of a load. Related to the structural state of the pavements.
ADT	Parameter	Average Daily Traffic. Represents the loads due to the traffic
Type of Pavement	Characteristic	Defines the characteristics of the material that composes the pavements.
Texture	Characteristic	Determines the drainage capacity and the noise. It is related with the security and the comfort.
Maintenance works		Projects of rehabilitation or improvement of the pavements. They inform into the modifications made on the original characteristics of the pavements.

Figure 3.9: Frías & Chaparro (2008)

3.3.8 Pave Plan Real Time PMS (Sonoma County)

Sonoma County PMMS tool is another GIS data model crafted with the ArcGIS for the integration and real time access to StreetSaver pavement information. The StreetSaver is a database comprising partitioned streets into paving sections, in real time, making it possible to highlight a particular road pavement section on the GIS map, . in which case, the roadway requiring urgent maintenance can be identified and shown on-screen in graphical dimension (Elhadi, 2009).

The integrated GIS-PMS tool can support County management in the identification of deteriorated road pavement sections, in real time, using a Web-based map interface. It simplifies the old PMS capabilities of the StreetSaver, which was designed by the Metropolitan Transportation Commission, MTC. This application came in the form of tabular datasets and reports, without on-screen visual information. Prints of maps had to be made for visual interpretation (Saunders, 2005).

A real time PMMS synchronises visual and tabular information using the ArcSDE geo-database technology and Microsoft SQL Server database. The application ensures managerial access to recent pavement distress maps and budget scenarios. Interfacing departments of planning, public works and finance is achieved along with a better understanding of road pavement problem areas (Saunders, 2005).

3.3.9 Visual IMS: GIS Integrated Infrastructure Management System

The Visual IMS optimises the GIS unique features of analysing spatially a voluminous variety of data and information, and presenting results graphically. In terms of road pavement management, Visual IMS outlines the framework of the system, develops generic models using mathematical techniques, and seeks potential application of new technologies and GIS integration (Haas et al., 1994).

GIS applications provide the mechanism for manual data sharing, automatic data sharing, standardization of data, standardization of analysis procedures, policy and decision-making integration, and integrated systems. This is brought to the next level of Visual IMS which creates a fully integrated tool which allows for the free flow of information, elimination of redundant data, better solutions, and cost reduction in system development and maintenance of road pavements. That means independent system components are linked together through a single application and process (Zhang et al., 1998).

A crucial dimension of this application would be the functional area of decision prioritisation. The application Visual IMS is positioned to predict future performance; to prioritize candidate M&R activities; to coordinate these M&R activities among subsystems; to provide financial estimates and calendar M&R; and to optimize funds allocation among the different subsystems (Zhang et al., 1998).

Figure 3.10 presents the result of this integration, which is characterised as a generic application. It is user friendly with its graphical user interface or the GUI technology; it can cope on various client or server structures, and it is completely portable on both machines under DOS or Windows operating systems and workstations.

Concept of an integrated infrastructure management system

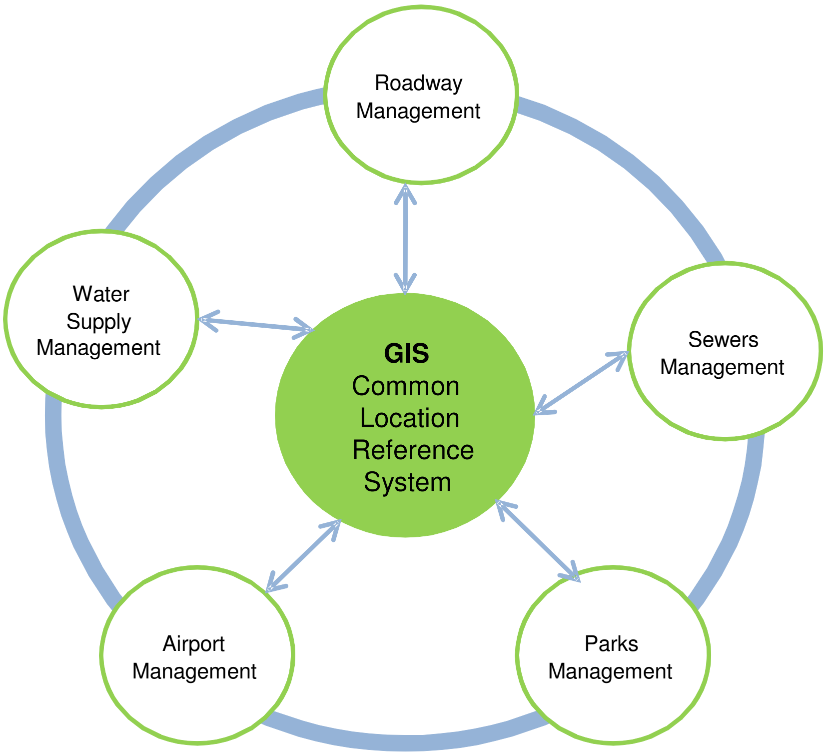


Figure 3.10: Zhang et al (1998)

3.3.10 Pavement View Software: North Carolina Management System in GIS

Inner road pavement management is described and developed essentially at the level of network; and on a project level. A constraint is that different types and volumes of information are required for the purpose of project and network level, for it to become an effective decision support tool (Haas & Hudson, 1978). The information stored at the network level is primarily for decision prioritisation of street segments that would need project level inspections for confirmation of M&R urgency. In data collection, the primary concern is that too much information causes a PMMS to fail or be discarded or discontinued (Elhadi, 2009).

Engineers use five different data types at the network level: distress, rutting, ride, geometrics, and surface friction. For asphalt concrete pavements, it includes patching, cracking, potholes, surface defects and surface deformation. Cracking is a frequent reason for pavement segment deterioration and failure (Shahin et al., 1990).

Pavement condition assessment by performing a 'windshield inspection' is conducted on a moving at near normal driving speed and data collected is stored in a pavement management database called CarteGraph Pavement View. This tool allows ease and accuracy of pavement inventory, inspection and PMMS information. A categorical inventory of paved and unpaved passages, pavement segment information, multiple imaging, videos, CAD files, and documents about pavement segment type, materials, dimensions, and geometry details are provided (Elhadi, 2009).

The Pavement View software calculates the overall condition index, or OCI, using the five category ratings on each road segment, with percent rating from 0% to 100%. Potential budgets are made out once candidate pavement segments have been identified for M&R. Pavement sections that require extensive technical assessment are scheduled for Project-Level inspection. The benefit of this application is that it provides the capacity to the entire Network in a reasonable period of time. Information is easily accessed by the public in map formats, which categorise each road segment of failed, failing, good, excellent, state road, and no rating. These files are linked to the city GIS network for other utility department PMMS as read-only files (Elhadi, 2009).

3.3.11 Road Measurement Data Acquisition System (ROMDAS)

ROMDAS is a Pavement Maintenance Management System that is GIS dependent. The software application implemented in the city of Abu Dhabi Island evolved from traditional tabular-data input and output databases. This tool avails of the GIS capabilities in geographical information and spatial analysis which are remarkably practical and appropriate for the nature of the road networks. It integrates statistical applications, pavement condition and management analyses on a map of the highway network, with lively colour coding of road pavement sections, and making graphical map interfaces possible and easy to interpret (Parida, 2005).

Abu Dhabi Island main roads network

Figure 3.11: Elhadi (2009)

Figure 3.11 shows the Abu Dhabi Island infrastructure network which forms a lattice system in blue stripes. The road is described as cutting across longitudinally through the island. Even numbers are assigned to the longitudinal roads while roads running across the island are assigned odd numbers. A start road in both directions shapes a central 'T'. Across the island, roads run along the end of the island furthest away from the mainland. Longitudinal roads start from the Airport road which is located in the middle of the Island. This sets apart the east and west zones. The entire stretch completes 2,100 km-lanes of road into three networks: Main Roads, Sector Roads and Internal Sector Roads (Kunka et al., 2005).

ROMDAS measurements use results from two tests: a roughness survey from Global Positioning System (GPS) test locations, and the Falling Weight Deflection Determination or FWD translated into International Roughness Index (IRI) on left and right wheel paths. The gathered information includes survey ID, road description, speed, stations and GPS coordinates (Elhadi, 2009).

Surface deviation from a true planar surface having qualities and dimensions that affect ride quality and vehicle dynamics is roughness. The Standards of the Vehicles-Pavement Systems, or ASTM E867, is an expression of irregularities in the pavement surface that adversely affect the ride quality in a vehicle. Roughness is a trade-off factor involving road quality versus user cost in delay, fuel consumption and maintenance costs (Moore, 1998).

Roughness is also a crucial measure of pavement performance which can be quantified by two distinct approaches: Present Serviceability Rating or PSR, and International Roughness Index or IRI. The World Bank developed the International Roughness Index in the 1980s. A standardised roughness measurement uses the commonly recommended units of meters per kilometre or m/km and millimetres per meter or mm/m, and is based on the average rectified slope, ARS (Elhadi, 2009).

The principles of Falling Weight Deflection or FWD and measurement techniques are adopted for road pavement work. A non-destructive, deflection testing equipment is either: a static deflection, a steady state or sinusoidal deflection, and an impact load deflections. Testing in this particular case was conducted for two up to four lanes dual carriageway at 100 m intervals, and performed at nights at appropriate temperatures to avoid traffic flow disturbances (AASHTO, 1993).

The exercise is straightforward:a set of weights is dropped onto rubber buffers and the impact load is transferred onto the road pavement through loading plates. From the centre of loading, deflections at various distances are jotted down by geophone sensors and analysed for configuration and magnitude of the deflection basin to measure the strength of the pavement structure (AASHTO, 1993). Elhadi (2009) quoted Muench (2003), who stated that the test completes a set of parameters including distance, air temperature, surface deflections, applied load, and pavement surface temperature that are measured at each testing location.

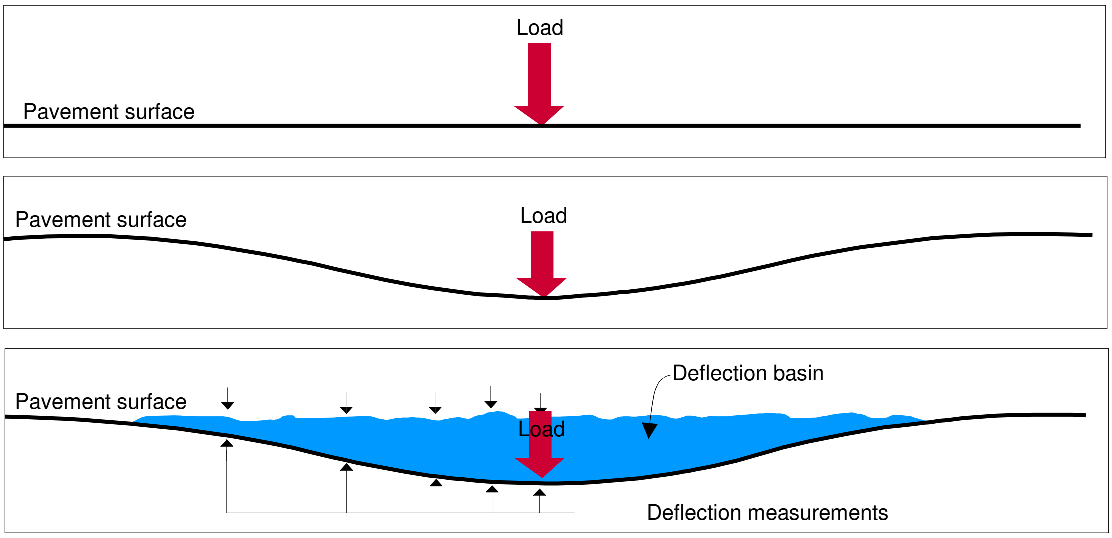


Figure 3.12: Deflection: deflection basin (Elhadi, 2009 after Muench, 2003)

Figure 3.12 is an illustration of the FWD, where a road pavement section is subjected to the load, the pavement yields and a deflection basin is created. Deflections at various distances from the centre of loading are recorded by geophone sensors (AASHTO 1993).

Data Collection Limited designed the ROMDAS in the 1990s. The tool includes a hardware device and software, which are configurable and operable in recording mode, indexing mode, and playback mode. ROMDAS was used mainly for data collection purposes because of its versatility, affordability and the fact that this equipment is completely portable for collecting data on roads, pavements, and traffic conditions (Elhadi, 2009).

ROMDAS measurements clearly state that roughness is not the single parameter in consideration in the design of PMMS, as the structural capacity parameter of FWD, visual parameters and M&R history also contribute to the decision prioritisation as well as the strategy of approach and treatment methods.

3.4 Other Applications of PMMS

3.4.1 Pavement Surface Evaluation and Rating (PASER)

PASER is an index rating system between 1 and 10 for the condition of roads developed by the University of Wisconsin. A rating of 10 is excellent and a rating of 1 is a fail. It is subjective in terms of evaluation and differences of opinion can occur. Nonetheless, prioritisation of road improvement is based on several factors apart from PASER. It considers road classification, accident history, location in system, and traffic volume. The RMMS is drawn after the PASER is determined, showing where effective care is most needed on the roadway pavement based on the rating identified. Typically, those with severe maintenance problems are given priority. Patching, ditch clearing and line stripping are performed as routine (Kmetz, 2011).

SURFACE RATING	VISIBLE DISTRESS	GENERAL CONDITION & TREATMENT MEASURES
10 Excellent	None	New construction
9 Excellent	None	Recent overlay, like new.
8 Very Good	No longitudinal cracks except reflection of paving joints. Occasional transverse cracks widely spaced 40' greater.	Recent sealcoat or new cold mix. Little or no maintenance required.
7 Good	Very slight or no ravelling, surface shows some traffic wear. Longitudinal cracks open ¼" due to reflection or paving joints. Transverse cracks open ¼" spaced 10" or more apart, little or slight crack ravelling. No patching or very few patches in excellent condition.	First signs of aging. Maintain with routine crack filling.
6 Good	Slight ravelling loss of fines and traffic wear. Longitudinal cracks open ¼" spaced 10' or more apart, little or slight crack ravelling. Slight to moderate flushing or polishing. Occasional patching in good condition.	Shows signs of aging. Sound structural condition. Could extend life with sealcoat.
5 Fair	Moderate to severe ravelling, loss of fine and course aggregate. Longitudinal and transverse crack open ½" show signs of slight ravelling and secondary cracks. First signs of longitudinal cracks near pavement edge. Transverse cracking and first signs of block crackling. Slight crack ravelling open ½'. Extensive to severe flushing or polishing. Some patching or edge wedging in good condition.	Surface aging. Sound structural condition. Needs sealcoat or thin non-structural overlay less than 2"
4 Fair	Severe surface ravelling. Multiple longitudinal and	Significant aging and first

	transverse crackling with slight ravelling. Block cracking over 25-50% of surface. Patching in fair condition. Slight rutting or distortions 1” deep or less.	signs of need for strengthening. Would benefit from a structural overlay 2” or more.
3 Poor	Closely spaced longitudinal and transverse cracks often showing ravelling and crack erosion. Block cracking over 50% of surface. Some alligator cracking less than 25% of surface. Patches in fair to poor condition. Moderate rutting or distortion 1” or 2” deep. Occasional potholes.	Needs patching and repair prior to major overlays. Milling and removal of deterioration extends the life of overlay.5
2 Very Poor	Alligator cracking over 25% of surface. Severe distortions over 2” deep. Extensive patching in poor condition. Potholes.	Severe deterioration. Needs reconstruction with extensive base repairs. Pulverization of old pavement is effective.
1 Failed	Severe distress with extensive loss of surface integrity.	Failed. Needs total reconstruction

Figure 3.13: PASER Rating Scale (Transportation Information Centre, University of Wisconsin, 2002)

3.4.2 Network Optimisation System (NOS)

The NOS model was developed as a cost minimisation linear programming method which brings pavement M&R to minimum levels for a particular planning period while quality standards on the network are maintained (Wang et al., 1994). The application generates the probability of transition between two pavement conditions, using four factors of roughness, cracking, cracking change and index to first crack. A severity level either high, moderate or low, is assigned to each factor. When the application is employed on 15 different road pavement sections, the NOS model extrapolates from these sets of probability conditions a number of M&R actions for each candidate road pavement to be treated (Orabi, 2010).

One observation using the NOS application is that crack changes per year may not be an appropriate indicator as regards the exacerbation of pavement deterioration, because the degree of distress development does not increase as the pavement deteriorates. A design limitation is that the future state of pavement condition is based solely on its current state, and does not include history data in the transition probability matrix (Orabi 2010; Wang et al., 1994).

The NOS application is implemented in Saudi Arabia (Harper & Majidzadeh, 1991), Holland, Finland, Kansas, Hungary, Australia and Alaska (Golabi & Pereira, 2003). It runs in a specific native 32-bit OS/2 code developed by the Universities of Arizona and Arkansas civil engineering departments.

3.4.3 Pavement Performance Prediction Modelling (PAVER)

PAVER is an application used typically in the determination of pavement M&R requirements. This system relies on the family method as an orientation of the process which does the following (Shahin, 2005):

- examines pavement sections with the same work needed and similar traits that affect pavement performance, traffic, weather, or maintenance concerns;
- data are filtered;
- then data outlier analysis is performed;
- the family model is generated; and
- sample pavement sections to the family model are assigned.

PAVER is based on the Pavement Condition Index (PCI) evaluation using a range ratings from 0 to 100, translating to a range between failed and excellent (D5340-98). The process begins by identifying the type of pavement distress in terms of extent and severity, combined by the deduct value curves. Sample units are selected for inspection through digital imaging. The result is the distress figure on the overall condition of the pavement (Shahin, 2005).

This application was developed by the American Army Construction Engineering Research Laboratory (USACERL) and its purpose is essentially to optimise the use of funds. It is typically used by airport pavement management agencies across the globe (D5340-98). A critique on the PAVER model by Fwa and Shanmugan (1998) notes that the application conceals various contributing effects of distress. The procedure of pavement treatment starting from the worst first, does not account for the assumed benefit from the spend either (Bemanian, 2007).

Figure 3.14 below illustrates the different types of maintenance needs involved with the maintenance of pavement. Asphalt life cycle is affected by routine maintenance, where if routine maintenance is ignored, the life costs increases dramatically. In Figure 3.14, pavement life with routine maintenance is represented by the blue lines, while pavement life without routine maintenance is represented by the red lines.

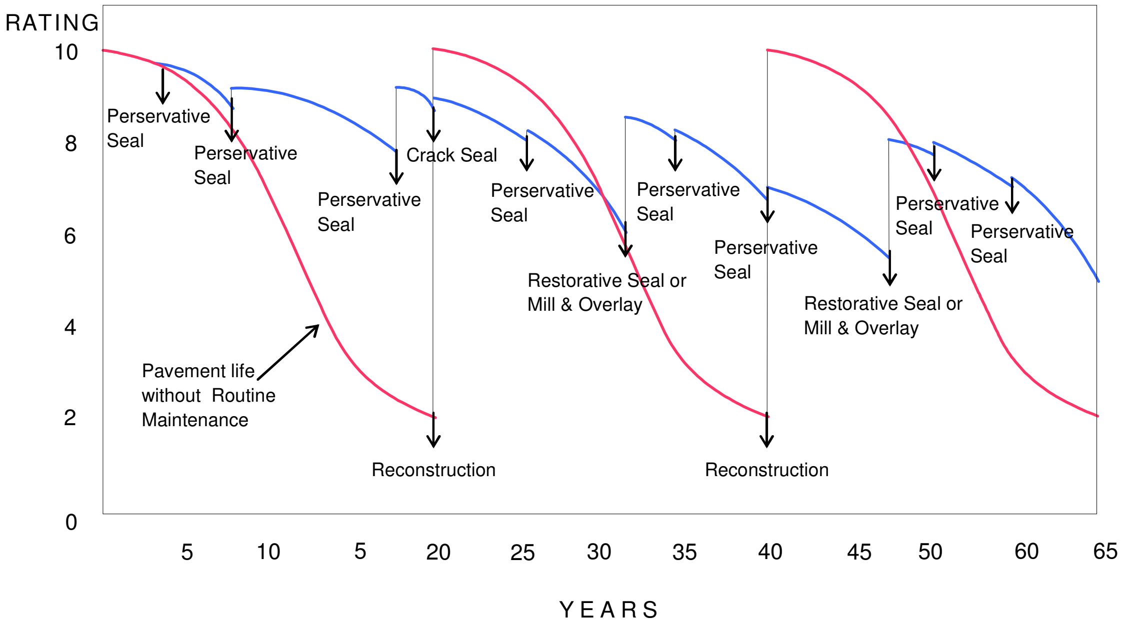


Figure 3.14: Asphalt Life Cycle, Effects of Routine Maintenance (Flintsch et al., 2004)

In the PAVER system, 19 distress items are identified for PCI computation. These include: alligator cracking, bleeding, block cracking, bumps and sags, corrugation, depression, edge cracking, reflection cracking, lane or shoulder drop off, long and trans cracking, patching, polished aggregate, potholes, railroad crossing, rutting, shoving, slippage cracking, swell, weathering and ravelling (Shahin & Kohn, 1981).

3.4.4 PAVENET (SINGAPORE)

As a first integrative application to solve PMMS, PAVENET is a single objective application on a pavement segment based model designed by the Singapore National University. The special characteristic of the PAVENET application is the exceptional branch and bound algorithm which is fully reliable in multi-year road pavement planning. The capability to render solutions to a particular road pavement section is an additional benefit. A rank-based priority scheme of weights is integral to the tool (Fwa et al., 1994).

PAVENET is a reliable alternative to the Arizona system with a distinctive feature that associates M&R actions with road segments in such a manner that it clearly identifies the segments of the road network where M&R actions should be applied (Ferreira et al., 2002)

The application is designed to minimise spending at optimal service by examining extreme alternative M&R actions, from doing nothing and structural overlay. The decision prioritisation specifies that the nature of action relies on the distress parameter values taken up. Nonetheless, exceeding the warning levels is not allowed (Goldberg, 1989).

3.4.5 Inter-level Interaction through Multi-agent Systems

The work of Chan et al (2004) seeks to justify the contradictions between jurisdiction levels of pavement management concerning several factors in varying degrees, which can be technical, social, economic, or political in nature. The usual scenario is a central authority that determines a policy that effectively incorporates all jurisdiction networks. In this way, the policy framework established for all network levels to carry out by themselves, constrains decision making within this set of parameters. It could be said that decision making criteria at project level are curtailed by higher management levels, which is observed as a process of succession optimisation. Typically, decision making at each management level is measured independently, thus the limitations at higher management levels are treated as set controls, which includes quality requirements and budget availability. In circumstances where several networks are linked by global funds, it is uncertain that M&R activities reach optimal levels.

The objective of the design is to take into account the opposing goals of decision makers at different management levels. The way to integrate agency workflow processes so as to arrive at a decision is shown in Figure 3.15.

Inter-level interaction through multi-agent systems is a model which relies on artificial intelligence dimensions to simulate an interactive PMMS for road pavement, interfacing the central administration and regional highway agencies. This solution considers the different objectives at different pavement management levels. It uses a hypothetical problem and a two-phase approach, allocation principles that combine what is needs-based, and an equation based system (Chan et al., 2004).

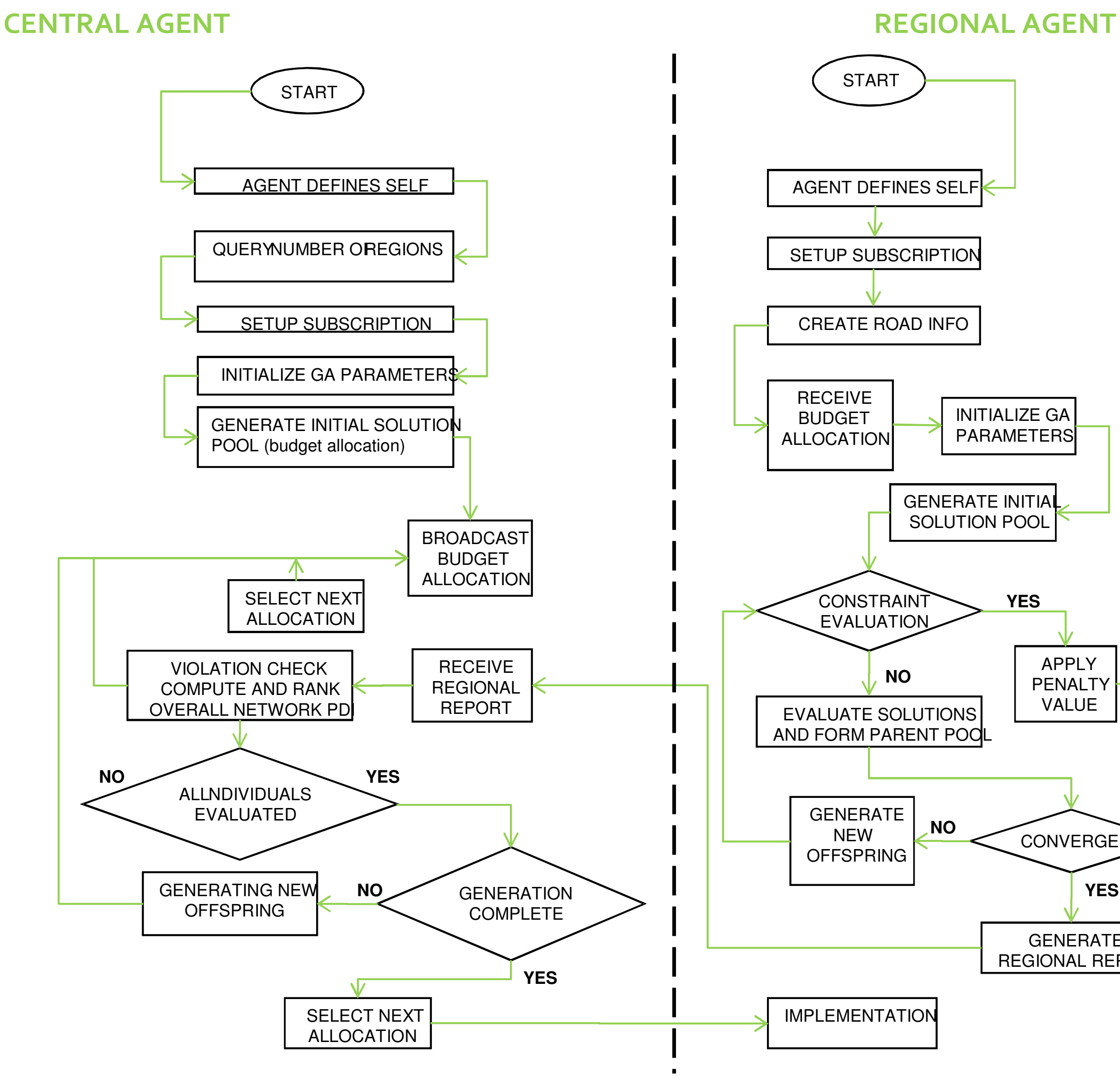


Figure 3.15: Flowchart for agent interaction and decision-making process (Chan et al., 2004)

The mechanism employed separates the optimisation process into two sequential stages. The first concerns each management level and the second considers different fund-allocation strategies by the central administration. Thus it analyses the needs and funding requirements of regional agencies as regards the state of network pavement conditions, the objective function, and the operational and resource constraints of a particular region. An optimal pavement-maintenance strategy is extrapolated for a particular maintenance budget. This strategy is correlated via database with the level of maintenance budget for all the regions concerned, and is repeated. For maintenance strategies integrating regions, a central administration system objective-function value for the entire system-wide road network can be derived (Chan et al., 2004).

This application synthesises and furthers the knowledge contributed in several decomposition efforts:

1. Optimisation of the network decision making process by incorporating faculties for fund allocation on different road hierarchies using the Dantzig–Wolfe decomposition algorithm (Alviti et al., 1994);
2. Road pavement optimisation performed at the planning level concerning fund allocation for various road hierarchies, achieved by harmonising sub-problem activities against the available resources (Wang et al., 1994);
3. Other applications on decomposition algorithm for hierarchal PMMS on road pavements (Worm & Harten, 1996).

For interregional road pavement fund allocation, a formula-based allocation approach is commonly used (Heggie & Vickers, 1998). Road-network characteristics are interpolated in the derivation of a formula-based allocation system. The set parameters include volume of traffic, length of the road network, number of registered vehicles, and ability to pay (Chan et al., 2004; Gáspár, 1994). The application here employs a formula calculated in proportion to the regional road length to the total road length of all regions. In this way the percentage of funds Pr to be allocated to region r can be expressed as per the equation below:

$$P_r = \left(\frac{\sum_j^n \ \mathrm{L}jr}{\sum_{r1}^{R} \ (\sum_j^n \ \mathrm{L}jr)} \times 100\% \right)$$

Where

L_{jr} = length of road segment j in region r

N = the total number of road segments in the region considered

R = total number of regions involved

3.4.6 Pavement Condition Evaluation System (PACES)

The application was designed by Georgia Department for Transport (GDOT) in 1986 specifically to log the severity and extent of various types of pavement surface distresses upon survey. PACES set the standard procedure on pavement condition assessments and the rating computations on distress conditions. Procedures on data collection and M&R rehabilitation treatments were set out.

Eventually this developed into a prioritisation framework where unacceptable pavement conditions come first. Pavement condition ratings are assessed by engineers based on traffic conditions, safety concerns, and surface distress. Candidate rehabilitation projects are then scheduled as to fund availability and contractors' workload, and those tasks delegated as internal work depending on district resources, thus delivering a reasonably good result, except that this could be improved through IT based PMMS. Advances in the application capabilities are that it now can (Tsai et al., 2001):

1. facilitate data integration of disparate databases through a standard common location identification system using the Linear Reference System (LRS);
2. provide databases to support temporal analyses with time reference information;
3. improve field data collection efficiency and quality;
4. develop statistical analyses and report generation capabilities;
5. provide an accurate prediction of the deterioration rate of pavement and development of performance forecasts; and

6. develop knowledge base systems (KBS) which capture and retain the expert knowledge necessary in diagnosing pavement distress and deciding a fitting rehabilitation treatment that is inherent mostly to senior engineers.

3.5 Shortcomings of GIS and Maintenance Systems

3.5.1 Shortcomings of GIS

Graeff & Loui (2008) identified some technical limitations with the application of GIS with regard to inaccuracies of the outputs of layering and digitisation, and listed three main problems with:

- The quantisation of continuous values;
- The resolution of image samples; and
- The combination of data in incompatible formats from various sources.

GIS requires a tremendous amount of data input to perform effectively for some tasks, however, more data input could cause errors in the location of data points. As multiple data is collected from multiple maps, this could create discrepancies between maps (Graeff & Loui, 2008).

3.5.2 Shortcomings in Current Maintenance Systems Based on GIS

The systems currently used in prioritising road maintenance are mainly based on the road condition, while some systems are based on factors such as daily traffic, road condition, and available budget. However, no standard factors have been adopted in local road authorities to be considered in prioritising road maintenance.

There is a need to consider more factors that affect the decision making process. This research investigates the most significant factors affecting the prioritisation of road maintenance in the UK as a first step to identifying those factors.

3.6 Suitability of GIS for this Research

Ibraheem and Falih (2012) stated that GIS is a suitable choice to base a pavement management system due to the spatial nature of road data, where GIS has the capability of storing, integrating, mapping, displaying, querying, and spatially analysing road data.

Shrestha and Pradhananga (2009) developed a GIS-based road maintenance management tool, which has demonstrated the efficiency in decision making regarding maintenance prioritisation of road networks.

Moreover, Adeleke et al. (2015) conducted a study on GIS as a support tool for pavement maintenance strategy selection and concluded that the use of GIS in pavement management has proved to be successful due to its capability of data analyses, query, and visual representation. The adoption of GIS leads to a better management of road maintenance (Yunus and Hassan, 2010).

Due to the constraints of budget, time and other factors, road maintenance planning is very challenging. The spatial nature of road components complicates the decision making process on priorities. However, applying GIS which is a powerful tool that can analyse and manipulate spatially distributed data can make the process easier (Pantha et al., 2010).

From the above review of the literature, it is evident that there is a solid agreement that GIS has a major advantage in being able to collect, archive, and analyse road data. Another acknowledged advantage of GIS is its ability to handle spatial data and visualise it using maps.

GIS is therefore suitable for tackling problems with spatial data and predicting, which are at the centre of pavement maintenance prioritisation and decision-making.

3.7 Pre-refined Conceptual Model

The pavement maintenance priority model has been developed and enhanced from its first step presenting in a conceptual model into a final developed model through continuous reviewing of literature, conducting a questionnaire survey within local road authorities, and organising interviews with professionals from local road authorities.

These methods have been used to identify and rate influencing factors, and to collect experts' feedback for rated factors to help developing the proposed model. This helped the researcher to identify key parts of the proposed model, evaluate the appropriateness of the proposed model, identify important factors that should be included in the development of the model, and finally, to decide required amendments and improvements that might be useful to enhance the developed model.

The research went through an evaluation process through an extensive review of recent pavement maintenance literature and capturing feedback from the research participants.

Chapters 4 and 5 provide more details of how the adopted methodology of the research helped to develop the proposed model for pavement maintenance priority to be more practical and useful for implementation and application in pavement maintenance projects.

Chapter Four

Research Design and Methodology

4.1 Introduction

In describing the types of research, Collis and Hussey (2009) argue that different types of research can be classified according to the purpose of the research; the process of the research; the logic of the research; or the outcome of the research (Ziad, 2009).

Classifying research according to the purpose for which it is undertaken is by considering the reason why the research is being conducted, and here there are four different types: exploratory, descriptive, analytical or predictive research. Based on the process of the research, which deals with the method of collecting and analysing the data, the classification results in qualitative or quantitative types; the logic basis of classification means either moving from the general to the specific or vice versa, and classifies research into deductive or inductive types; and finally, based on the outcome of the research means whether the research aims to solve a particular problem or to make a general contribution to knowledge and there are two types, applied or basic research (Ziad, 2009 cited Collis and Hussey, 2009).

However, Hammersley (1993) classifies research into scientific research and social research, whereby the scientific research deals with natural science methods of investigating physical phenomena with the key elements being quantitative measurement and experimental or statistical manipulation of variables; while social research deals with how people interpret their surroundings and act on the basis of those interpretations (Ziad, 2009 cited Hammersley, 1993).

Social research is the most relevant approach to this research project because no experiments are conducted and no measured physical phenomena are involved; instead, the proposed research is mainly about investigating people's perceptions and attitudes where variables are not controllable and where the social research methodologies are most appropriate for collecting and analysing the data. In addition, social research, according to de Vaus (2001), requires a clear design or a structure to be decided upon before the data collection or analysis activities can commence. De Vaus (2011) also maintained that the purpose of the research design is to ensure that the evidence collected will enable the researcher to answer the research questions as clearly as possible. Obtaining the relevant evidence therefore involves specifying the type of evidence needed for answering the research questions, testing a theory or describing a phenomenon in a convincing way (Ziad, 2009 cited de Vaus, 2001).

In this context, de Vaus (2001) compares undertaking social research to constructing a building, whereby before a builder can develop work plans or order materials, they must first establish the type of building required, its use and the needs of the proposed occupants. The work plans will result from this. In the same way, in social research deciding on the type of evidence required is fundamental before issues such as data collection techniques and design of questions for questionnaires are considered (Ziad, 2009 cited de Vaus, 2001).

However, Saunders et al (2012) classified research into six stages and labelled the model, which he presented as 'the research onion' (Figure 4.1). Saunders et al (2012) divided the research to include philosophy; approach; methodological choice; strategies; time horizon; techniques and procedures.

This chapter will first explore some of the literature dealing with research structure design and methodology before adopting, justifying and implementing specific research design and methodologies. The precise research design for this research will therefore establish the following research components:

- Reviewing the literature for existing pavement maintenance management practices;
- Collecting data for the most significant factors affecting pavement maintenance priority rating;
- Collecting data to justify the priority rating of the most significant factors;
- Data Analysis Methods;
- Collecting case study data from the Surrey County Council;
- Development of a GIS-based Model; and
- Results Analysis, Assessment and Validation.

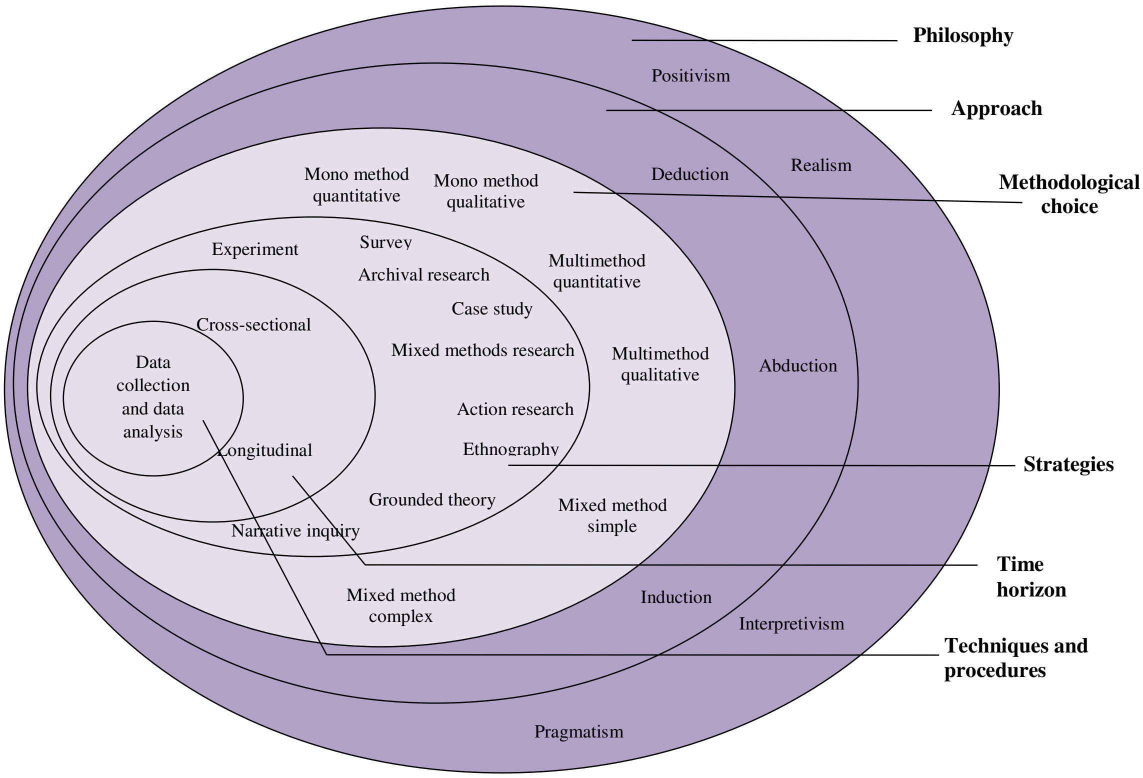


Figure 4.1: The Research 'Onion' (Saunders et al., 2012)

4.2 Research Philosophy

In dealing with the conceptual issues of research, Saunders et al (2012) refer to research philosophy as an overarching term relating to the development of knowledge and the nature of that knowledge. According to Saunders et al (2012), there are four research philosophies: positivism, realism, interpretivism and pragmatism. Table 4.1 shows the comparison of the four research philosophies (Saunders et al., 2012).

According to Collis and Hussey (2009), there are two basic research paradigms or philosophies: positivist and interpretivist. The positivist paradigm is also referred to as quantitative, objectivist, scientific, experimental and traditionalist; while the interpretivist paradigm is also described as qualitative, subjectivist, humanistic and interpretive. Although considerable reasoning may be required to justify the suitability of a particular research paradigm, the two main paradigms should be seen as the two ends of a research continuum with the features and assumptions varying gradually as the research moves along the continuum (Ziad, 2009 cited Collis and Hussey, 2009).

	Positivism	Realism	Interpretivism	Pragmatism
Ontology: the researcher's view of the nature of reality or being	External, objective and independent of social actors	Is objective. Exists independently of human thoughts and beliefs or knowledge of their existence (realist), but is interpreted through social conditioning (critical realist)	Socially constructed, subjective, may change, multiple	External, multiple, view chosen to best enable answering of research question
Epistemology: the researcher's view regarding what constitutes acceptable knowledge	Only observable phenomena can provide credible data, facts. Focus on causality and law-like generalisations, reducing phenomena to simplest elements	Observable phenomena provide credible data, facts. Insufficient data means inaccuracies in sensations (direct realism). Alternatively, phenomena create sensations which are open to misinterpretation (critical realism). Focus on explaining within a context or contexts	Subjective meanings and social phenomena. Focus upon the details of situation, a reality behind these details, subjective meanings motivating actions	Either or both observable phenomena and subjective meanings can provide acceptable knowledge dependent upon the research question. Focus on practical applied research, integrating different perspectives to help interpret the data
Axiology: the researcher's view of the role of values in research	Research is undertaken in a value-free way, the researcher is independent of the data and maintains an objective stance	Research is value laden; the researcher is biased by world views, cultural experiences and upbringing. These will impact on the research	Research is value bound, the researcher is part of what is being researched, cannot be separated and so will be subjective	Values play a large role in interpreting results, the researcher adopting both objective and subjective points of view
Data collection techniques most often used	Highly structured, large samples, measurement, quantitative, but can use qualitative	Methods chosen must fit the subject matter, quantitative or qualitative	Small samples, in-depth investigations, qualitative	Mixed or multiple method designs, quantitative and qualitative

Table 4.1 Comparison of four research philosophies in business and management research (Saunders et al., 2012)

In addition, Collis and Hussey (2009) distinguish between the two terms "methodology" and "methods" and consider that methodology covers the overall research approach from the theoretical concept to the collection and analysis of the data. On the other hand, Collis and Hussey (2009) affirm that methods refer to the different means of acquiring and analysing the data, and that the paradigm decided upon at the start will greatly influence the methodology to be adopted (Ziad, 2009 cited Collis and Hussey, 2009).

When considering research paradigms, Collis and Hussey (2009) use the terms positivistic and phenomenological in preference to quantitative and qualitative respectively, because they argue that it is possible for a positivistic paradigm to produce qualitative data, and conversely, research with a phenomenological paradigm can generate quantitative data. Table 4.2 summarises the main features of the two research paradigms (Collis and Hussey, 2009).

Positivism tends to:	**Interpretivism tends to:**
Use large samples	Use small samples
Have an artificial location	Have a natural location
Be concerned with hypothesis testing	Be concerned with generating theories
Produce precise, objective, quantitative data	Produce 'rich', subjective, qualitative data
Produce results with high reliability but low validity	Produce findings with low reliability but high validity
Allow results to be generalised from the sample to the population	Allow findings to be generalised from one setting to another similar setting

Table 4.2: Features of the two main paradigms (Collis and Hussey, 2009)

Having decided on the overall paradigm to be adopted for the research, it is possible to adopt a mixture of methodologies and, in particular, methods of collecting and analysing the data. This enables the researcher to acquire a wider outlook on the research issues, and providing the researcher is able to collate the data sensibly, a more complementary view of the research will result (Collis and Hussey, 2009).

This view is supported by Jones (2004) who reviewed the theoretical background to the current sharp division between quantitative and qualitative methods, which, he argued, is based on a long philosophical tradition that has continued to form the present division between quantitative and qualitative methods in the social sciences. However, Jones

(2004) also accepted that although in practice many researchers combine quantitative and qualitative methods, some still doubt whether in empirical work the two approaches could be combined in a principled way as they amounted to different paradigms of research (Ziad, 2009 cited Jones, 2004).

Jones (2004) concluded that the divide between quantitative and qualitative methods is not fundamental and hides many of the common features between the two, and maintained that this conclusion is a release from the qualitative and quantitative divide. He further concluded that qualitative research and quantitative research are not competing paradigms but they are rather intimately connected, and represent different ends of this spectrum of research activity (Jones, 2004).

Collis and Hussey (2009), on the other hand, define business research in the broad sense as that research looking at organisations, public or private and commercial or not-for-profit, and their activities from the viewpoint of all the stakeholders. In this context, they argue that the positivistic paradigm is the prevailing approach for business research and in which case it is relatively easy to justify the corresponding methodologies to be adopted. However, increasingly the phenomenological approach is considered more appropriate for some business research and there may be qualitative elements of a positivistic approach, and in such cases justifying and explaining the methodologies adopted would be necessary (Collis and Hussey, 2009).

Additionally, Denscombe (1998) considers that in social research, the two approaches, quantitative and qualitative, represent indicators as to the kind of assumptions made and the nature of the research. That in practice research does not fall precisely into one approach or the other because good research is likely to use parts of both approaches; there is no distinct dividing line between the two approaches (Ziad, 2009).

4.3 Research Approach

Saunders et al (2012) classified research approaches into three categories under reasoning level: deductive, abductive and inductive approach. However, if a researcher starts with a theory that is developed from literature, and designs a strategy to test the theory, then a deductive approach is adopted; if the research starts with data collection to generate a theory, then an inductive approach is adopted; finally, the abductive approach is a combination of deductive and inductive (Saunders et al., 2012). Table 4.3 shows a comparison between the three approaches.

	Deduction	**Induction**	**Abduction**
Logic	In a deductive inference, when the premises are true, the conclusion must be true	In an inductive inference, known premises are used to generate untested conclusions	In an abductive inference, known premises are used to generate testable conclusions
Generalisability	Generalising from the general to the specific	Generalising from the specific to the general	Generalising from the interactions between the specific and the general
Use of data	Data collection is used to evaluate propositions or hypotheses related to an existing theory	Data collection is used to explore a phenomenon, identify themes and patterns and create a conceptual framework	Data collection is used to explore a phenomenon, identify themes and patterns, locate these in a conceptual framework and test this through subsequent data collection and so forth
Theory	Theory falsification or verification	Theory generation and building	Theory generation or modification; incorporating existing theory where appropriate, to build new theory or modify existing theory

Table 4.3 Comparison of three research approaches (Saunders et al., 2012)

However, Collis and Hussey (2009) classifies research into deductive or inductive types, based on the logic of classification, which means either moving from the general to the specific or vice versa.

4.4 Research Methodological Choice

Bryman (2012) classified research methodological choice as the following:

- Mono method: a quantitative or a qualitative method on its own
- Mixed method: quantitative and qualitative methods used together
- Multimethod: multiple use of methods in a way that either ‘quantitative only’ or ‘qualitative only’.

Johnson and Onwuegbuzie (2004) visualised research paradigms as being a continuum with qualitative research anchored at one extremity and quantitative research anchored at the other, and proposed mixed methods research as covering the large space in the middle area. They hence categorised mixed methods research as sitting in a third position, with qualitative research sitting on the left side and quantitative research sitting on the right side (Ziad, 2009 cited Johnson and Onwuegbuzie, 2004).

In presenting mixed methods research, Johnson and Onwuegbuzie (2004) therefore endorsed moving beyond quantitative versus qualitative research arguments because, they argued, both quantitative and qualitative research is important. However, the goal of mixed methods research is not to replace either of these approaches but rather to draw from their respective strengths and minimise the weaknesses of both in single research studies and across studies (Johnson and Onwuegbuzie, 2004).

4.5 Research Strategies

Denscombe (1998) suggests that there is no one right approach to take but rather that some strategies are more suited for tackling specific research areas, and that the strategy is chosen at the start of the research on a 'fitness for purpose' basis, as being the most appropriate for investigating the particular research problem at hand (Ziad, 2009).

Then again, Jankowicz (2005) uses a 'method' at a similar level in the research structure to the 'strategy' adopted by Denscombe (1998), and describes a research method as the organised and methodical way of gathering and analysing data such that information can be ultimately derived from such data. Jankowicz (2005) also differentiates between data and information in that data are "raw, specific, undigested and largely meaningless"; while information is the output after processing the data in order to reduce uncertainty, resolve queries and remove doubts (Ziad, 2009).

The following sections present some of the main research strategies:

4.5.1 Surveys

Collis and Hussey (2009) consider surveys in general to be a positivistic methodology, which involves a study of a population in order to draw inferences about certain aspects of the population. If the population is large, data are collected about a sample of that population, and if the sample is considered representative, then it may be possible to draw generalisations from the sample about the behaviour of the population. It is essential therefore when selecting a survey sample to ensure that it is representative of the population as far as possible and is not biased. There are different methods used for obtaining the data through a survey including questionnaires and face-to-face or telephone interviews (Collis and Hussey, 2009).

Collis and Hussey (2009) also divide surveys into two main types: descriptive surveys and analytical surveys. Descriptive surveys involve counting the frequency of a population in relation to a specific issue at a particular point in time or at certain specified time intervals, and these include customer attitude surveys in business. The object of analytical surveys is to determine the relationship between different variables (Collis and Hussey, 2009).

Denscombe (2010) defines the term ‘survey’ as a comprehensive or detailed view or the act of acquiring data by mapping. These two aspects are analogous to a geographical type of survey in the sense that the object is to map out the landscape or buildings to record details or features. In social research, the object of a survey is to map the social world to obtain the necessary data in order to understand specific aspects (Denscombe, 2010).

Denscombe (2010) believes that a survey is a research strategy, not a method, and a wide range of methods is available for collecting the data within this strategy including questionnaires, interviews, documents and observation.

4.5.2 Experiments

Experimental studies are a positivistic type of methodology according to Collis and Hussey (2009), and are conducted systematically either in a laboratory or in a natural setting. Laboratory experiments allow the researcher to exercise more control, and by manipulating the independent variables, the researcher can observe the effects on dependent variables. Confounding variables are those that tend to obscure the effect of other variables and these can be controlled in a laboratory setting. It is difficult to arrange laboratory experiments in business research and in practice such experiments do not represent the actual environment (Collis and Hussey, 2009).

Field experiments have the advantage of representing the real world to a greater extent, however, the experiments may still be difficult to establish and carry out and there is less control over the confounding variables. Another type of variable, which may be difficult to control in a field experiment, is the 'extraneous variable', which is any variable other than the independent variable which may still have an effect on the dependent variable (Collis and Hussey, 2009).

In addition, Jankowicz (2005) maintains that, in social research experiments, data are collected by closely observing a predetermined set of behaviours under controlled conditions, in order to understand an event or attribute the results to a general theory. Field experiments are therefore carried out if the researcher is familiar with the area being studied and the setting involved to be able to benefit from observing the identified variables which affect each other (Jankowicz, 2005).

4.5.3 Case Studies

Collis and Hussey (2009) classify the case study as a phenomenological methodology, and define it as an in-depth investigation of a particular example of a phenomenon. A 'unit of analysis' refers to the particular case with which the research problem is concerned and about which the data are collected and analysed, and the case study approach means that a specific unit of analysis is involved which can be a company, a group of employees, an event, a process or a single individual (Collis and Hussey, 2009).

Yin (2009) presented three main features of a case study:

- The aim of the research is to understand the event in a specific framework rather than to explore it;
- The case study limits are not determined by questions and notions included in the research; and
- Various methods for collecting the data are used, both qualitative and quantitative.

Collis and Hussey (2009) also identify some potential weaknesses of the case study approach, starting with the difficulty of arranging a suitable organisation and the lengthy time needed to complete the investigation. There is also the problem of deciding on the 'delimitation' of the study, which means deciding where the researcher should place the boundaries of the research. This is because an organisation does not exist in a vacuum but rather interacts with society and different stakeholders, and has a history, which can shape the understanding of the present. The researcher may therefore find it difficult to understand an event at a particular time without investigating what happened before and what may happen after (Collis and Hussey, 2009).

Denscombe (1998) identifies what a case study can do, that a survey in general cannot, which is to examine the issues in detail. A researcher's decision to dedicate all efforts to studying just one instance is a strategic decision and means that a greater opportunity is available to probe into things in more detail and find out about the things that would not otherwise have become obvious (Denscombe, 1998).

Denscombe (1998) emphasises that selecting the case study approach is a research strategy choice and does not dictate a particular method to use. This is in fact considered as strength of the case study in that a variety of methods can be used for collecting the data depending on the circumstances and the specific needs of the research (Denscombe, 1998).

Yin (2009) also classifies the case study as a research strategy for undertaking social science research, and identifies case studies as being the preferred strategy when "how" or "why" questions are being addressed, when the researcher has little control over events, and when the research is concentrated on a "contemporary phenomenon with real-life context".

Yin (2009), in addition, states that the case study, as a research strategy, is adopted to contribute to knowledge in many situations such as individual, group, organisational, social, political, and related phenomena and applied in diverse social science disciplines ranging from psychology and sociology to political science and planning. The need to adopt case studies therefore arises from the desire to understand complex social phenomena.

Yin (2009), however, refers to a common misconception amongst some researchers who consider that case studies are only suitable for the preliminary exploratory phase of research and cannot be used to describe or test propositions. Yin (2009) argues that many case studies are far from being only just an exploratory strategy, and also that case studies can be exploratory case studies, descriptive case studies or explanatory case studies; in the same way that experiments can be exploratory, descriptive and explanatory experiments.

Moreover, Yin (2009) refers to a general criticism of case studies as a research endeavour, in that case studies are often viewed as lacking research vigour and are therefore less desirable as a form of inquiry. However, Yin (2009) argues that this is only the case where the researcher has been “sloppy” and not adhered to systematic procedures, or permitted ambiguous evidence and biased views to influence the research findings and conclusions.

Yin (2009) therefore provides a rationale to the generalisation issues by arguing that for case studies, similar to experiments, it is possible to generalise to theoretical concepts and not to populations or on global scales, because case studies, in this sense, do not represent a “sample” and, in adopting case studies as a research strategy, the intention would be to expand and generalise theories (analytic generalisation) and not calculate frequencies (statistical generalisation) (Yin, 2009).

Three conditions were set out by Yin (2009), which determine when to use each research strategy, and these relate to the type of research question; the extent of researcher control over events and behaviours; and the degree of focus on contemporary rather than historical accounts.

Yin (2009) hence concludes that case studies are preferred for research dealing with contemporary events when the relevant behaviours cannot be manipulated by the researcher. Also, the case study has a unique strength in that it has the ability to deal with a full variety of sources of evidence including documents, artefacts, direct observation of the events under investigation, and interviews of the persons involved, and can be based on any mix of qualitative and quantitative evidence.

4.6 Research Time Horizon

It is important in designing a research to consider time horizon, which focuses to keep time within the limits of a research. Saunders et al (2012) defines two types of time horizon; cross-sectional and longitudinal. Cross-sectional is when the study of a particular phenomenon at a particular time is needed, whereas longitudinal is when the study is taken in series of tasks to enable the researcher to study change and development (Saunders et al., 2012).

Collis and Hussey (2009) defines cross-sectional study as a methodology used to investigate variables or a group of subjects in different contexts over the same period of time, whereas longitudinal study as a methodology used to investigate variables or a group of subjects over a long period of time.

4.7 Research Techniques and Procedures

Denscombe (1998) argues that certain research methods are better suited to some research strategies, such as the link between a survey and questionnaires, and that such links are founded on sound theoretical reasons. However, in social research within a specific strategy, there is still a degree of choice as to the methods to be used for collecting the data, and such choice is ultimately dependent on practical considerations such as timing, available resources and access to data. He also advises that while each method has its advantages and disadvantages with no one ‘superior’ method, the choice must be based on the most appropriate method for the research (Denscombe, 1998).

Jankowicz (2005) on the other hand, adopts the term “technique”, which he contrasts with the research method in that the technique is the specific “step-by-step” process of gathering and analysing the data in order to extract information from them.
Jankowicz (2005) grouped the main techniques under the following categories:

- Semi-structured techniques: these are open-ended and include conversations and individual interviews;
- Structured techniques: including the questionnaire and structured face to face interviews; and

- Additional techniques: including structured observational techniques and field experiments.

Jankowicz (2005) also affirms that structured techniques are not necessarily better or more scientific just because they tend to go well with quantitative analysis, but that what is important is the level of understanding possible as a result of the particular technique. He also argues that although unstructured interviews are often viewed as the imperfect version of interviews, structured interviews themselves are not guaranteed to be free from errors and can essentially be flawed and therefore cannot be used as a benchmark for other approaches (Jankowicz, 2005).

4.7.1 Data Collection

The following is a review of the most relevant data collection techniques:

4.7.1.1 Questionnaires

Collis and Hussey (2009) regard questionnaires as being suited to both the positivistic and phenomenological research methodologies, and describe a questionnaire as a set of thoroughly thought out and structured questions designed to draw out reliable responses from a selected group of participants. In a positivistic setting, closed-ended questions suitable for large scale surveys would be designed, which are compatible with computer analysis, while, in contrast, in phenomenological research the questions would be open-ended questions, which are not normally suited to large scale surveys. Questionnaires are also popular, relatively cheap and a less time consuming method of collecting data (Collis and Hussey, 2009).

The following important precautions have been recognised when adopting questionnaires for collecting the data (Collis and Hussey, 2009):

- All participants should be asked the questions in the same way and the researcher should ensure that participants also understand the questions in the same way.
- Participants should know the purpose and context of the questionnaire and this should be made clear in the questionnaire.

- Well-designed questions are vital for the reliability and the validity of the data obtained.
- Questionnaire presentation is also important to encourage the selected respondents to actually take part by completing the questionnaire and can also help with analysing the data at a later stage.
- Accurate instructions should be given as to the manner in which the questionnaire is to be completed and returned.
- The questionnaires should be given unique numbers to enable control, monitoring and follow-up of non-responding participants.
- The questions should be set out logically starting with general topics and tapering to detailed areas. Topics that are more complex should be filtered so that moving forward depends on answers given to previous questions.

Denscombe (1998) states that the data obtained through the use of questionnaires rely on written replies supplied by respondents; and for this reason the type of data obtained is different from those obtained through interviews, observation or document searches, in that data from questionnaire responses fall into two categories, ‘facts’ or ‘opinions’. It is essential that the researcher is aware throughout the process of whether the questions seek facts or opinions (Denscombe, 1998).

Denscombe (1998) clarifies this point further in that questions that seek factual data do not require the respondent's judgement but rather his/her accuracy and honesty in answering the questions. In contrast, questions seeking opinions, views, attitudes or beliefs require the respondents to disclose their own views, feelings and values by making judgements. In practice however, it is likely that survey questionnaires will include both types of questions to search for facts as to what is actually taking place and judgements or opinions about why respondents think things are happening in a particular way (Denscombe, 1998).

4.7.1.2 Interviews

Similar to questionnaires, Collis and Hussey (2009) regard interviews as being appropriate for both the positivistic and phenomenological research methodologies, and define an interview in the context of carrying out social research in terms of selected individuals or a group of individuals being asked questions in order to learn what they know, do, think or feel about a particular topic. Interviews can be conducted face-to-face, over the telephone or through the internet (Collis and Hussey, 2009).

Interviews conducted in a positivistic setting would tend to adopt the closed questions style, where the questions are pre-prepared, such as in market research surveys. However, in phenomenological research the interview may be unstructured where the questions have not been prepared in advance; or semi-structured where the interview is centred on a pre-prepared set of questions but allowed to flow freely as it is being conducted. Some of the disadvantages of the unstructured and semi-structured interviews include that they are time consuming, difficult to control and difficult to analyse later. Open-ended questions are more suitable for a phenomenological research and it is likely that probes will be used to investigate the subject in more detail (Collis and Hussey, 2009).

Collis and Hussey (2009) suggested appropriate circumstances where unstructured or semi-structured interviews could be used:

- When the researcher needs to establish the interviewee’s basis for forming certain opinions or beliefs;
- When it is an aim of the research activity to attempt to influence the respondent's practices by fully understanding such practices;
- When confidentiality or commercial sensitivity are an issue; and
- When it is felt that the respondent would be less likely to be truthful about an issue except confidentially and in a one-to-one setting.

Another important feature of unstructured or semi-structured interviews is that the questions asked and subjects discussed will be different for each interview depending on the direction the interview takes within the same issue. This feature is called ‘open discovery’ and is considered a strength of this style of interview, although the researcher will need to exercise some control over the emphasis and balance of the emerging issues (Collis and Hussey, 2009).

Several shortcomings have been identified with conducting interviews, generally including (Collis and Hussey, 2009):

- The lengthy process and expense involved;
- Access to suitable participants;
- The issue of confidentiality;
- The difficulty of ensuring that interviews are conducted in the same way, which entails asking as well as posing the questions in the same way;
- Difficulty of ascertaining that participants understand the questions in the same way;
- Effect of the interviewer on the process, which includes biases due to sex, race or class; and
- Difficulty avoiding getting answers based on the interviewee's expectations of what are considered 'correct' or 'acceptable' answers.

Notwithstanding the above disadvantages, interviews give the researcher the opportunity to ask complex questions, with follow-up questions to probe the issues further, which is not possible in the questionnaire method; a greater measure of confidence can be placed on the responses than in the questionnaire; and an account can be taken of the participant's attitude and behaviour and non-verbal communication perceived at the interview (Collis and Hussey, 2009).

4.7.1.3 Observation

Denscombe (1998) considers observation, as a method of collecting data, to be advantageous in that it does not rely on what respondents say they do or think but rather relies directly on what the researcher witnesses first hand as "direct evidence", and in certain circumstances observing events first hand is the best means of obtaining evidence. Observation research is classified into two main types; systematic observation which studies interactions in settings and mainly deals with quantitative data and statistical analysis; and participant observation which is used by researchers to gain access to the area being researched, either 'under cover' to study cultures and practice or openly, and mainly yields qualitative data (Denscombe, 1998).

Collis and Hussey (2009) agree that observation is suitable for both the positivistic and phenomenological methodologies, but state that observation can take place in either a laboratory setting or a natural setting, where a natural setting is defined as that which would still have existed had there been no research being conducted. Observation is performed in two main modes; participant observation where the researcher takes full part in the activity being researched and is able to experience, understand and interpret the practices, values and motives; and non-participant observation where the aim is to witness people's actions and reactions without the researcher being involved in the setting (Collis and Hussey, 2009).

Collis and Hussey (2009), however, identify some problems with the observation method including the difficulty of controlling variables in a natural setting; issues concerned with ethics, objectivity and visibility; and observer bias when different observers arrive at different conclusions (Collis and Hussey, 2009).

4.7.1.4 Document Search

According to Denscombe (1998), document search can be regarded as a distinct source of data, based either on library desk-studies, archive research or any other documents from which data can be derived. The major sources of data are written sources although visual and audio forms of documents also have a value even if used less in social research. The main sources of written documentary evidence for research include (Denscombe, 1998):

- Books and journals, which are considered the first source of research material for academic research, and the researcher needs to continually assess the quality, validity and relevance of each source.
- Internet and web sites, which are increasingly used; however, there are issues of credibility, authenticity and authorship which are difficult to ascertain so quality control needs to be exercised by the researcher when using internet sources.
- Organisations' records provide a valuable source of data because of the level of details available, which were originally created to ensure accountability, and include documents relating to policy, management, administration, commerce and transactions.

- Letters and memos, which provide help to clarify events and reasons for decisions taken in organisations, although the drawback is that letters exchanged between people assume a certain level of background knowledge about the subject.
- Diaries, which are important records of events that have already happened, are “retrospective accounts” and highlight people’s thoughts. Diaries have three important features from the research view point: they are a factual log of previous events; they are records of important events and significant incidents; and they provide the writer’s personal interpretation and comments on such events.
- Government publications and official documents, which are to certain extent considered authoritative, objective and factual, and although this is true in certain cases where they contain valuable data and statistics, the researcher must guard against politically motivated publications where the objective is to promote a particular point of view.

4.7.2 Data Analysis

Jankowicz (2005) contrasts the positivist versus interpretivist characteristics on the one hand with the qualitative versus quantitative data and analysis on the other. Traditionally, the positivist approach has been associated primarily with quantitative methods, based on measurements and numbers, with qualitative methods only used during the initial investigative stages, while the interpretivist approaches primarily deals with qualitative methods. Nonetheless, it is true to say that both quantitative and qualitative methods can be used within either of the two rationales, positivist and interpretivist, depending on the nature of the research (Jankowicz, 2005).

Collis and Hussey (2009) support this view and distinguish between the use of positivistic versus phenomenological research paradigms and the use of quantitative versus qualitative methodology, and affirm that it is possible for a positivistic paradigm to generate qualitative data although it is common to link positivism with numbers and measurements.

In addition, Denscombe (1998) considers that the distinction between qualitative and quantitative research is not precise and that such distinctions are based on oversimplification and not on real world social research practice.

After collecting the data, the researcher will be ready to start the data analysis stage and, as Collis and Hussey (2009) state, the choice between the various data analysis techniques depends on whether the data are quantitative or qualitative, or a combination of both. In a positivistic paradigm research, the data are likely to be mainly quantitative in the form of numerical values that will require some form of statistical analysis. Numerous computer statistical software are available, including those especially developed to provide statistical analysis for social research, and allow the researcher to carryout statistical tests and analyses to a greater extent and scope, as well as to present the results in table and chart formats that also facilitate the better interpretation of the results (Collis and Hussey, 2009).

Different authors distinguish between two types of data analysis in dealing with quantitative data: 'exploratory analysis' or 'descriptive statistics' which is used to present summaries, describe and exhibit the data; while 'confirmatory analysis' or 'inferential statistics' draws conclusions about a population based on the quantitative data collected from a sample. In addition, there is a distinction within the confirmatory analysis category between 'non-parametric' and 'parametric' techniques where parametric techniques are considered more important because they are more powerful since they are able to compare sample statistical results with the population parameters providing the data have a 'normal distribution'. In contrast, the more general 'non-parametric' techniques can handle 'skewed' data (data not normally distributed), but are less reliable (Collis and Hussey, 2009).

The choice of statistical technique or procedure depends on whether exploratory or confirmatory analysis is required and on whether the data are normally distributed or skewed. In addition, the number of variables to be analysed simultaneously is an important factor in the selection, whether the analysis is 'univariate' (single variable), 'bivariate' (two variables), or 'multivariate' (more than two variables) (Collis and Hussey, 2009).

Phenomenological research may also generate quantitative data although it may not be necessary to analyse the data in this case using statistical tools. The methods for analysing qualitative data have been grouped by Collis and Hussey (2009) into two main categories, quantifying methods and non-quantifying methods. Selecting the most appropriate method depends on whether the research has a positivistic paradigm, in which case a formal quantifying method is used; or a phenomenological paradigm, where the researcher may wish to use an informal quantifying method although it is likely that non-quantifying methods will be used (Collis and Hussey, 2009).

Collis and Hussey (2009) also argue that whilst the two main paradigms discussed earlier, positivistic and phenomenological, represent the two extremes in a continuum, it may be possible or even beneficial for research to contain a blend of methodologies including both qualitative and quantitative data collection methods, such as a survey questionnaire to obtain quantitative data and interviews for qualitative detailed insight (Collis and Hussey, 2009).

4.7.2.1 Informal Methods

This method involves assessing the data informally for patterns or repeated behaviour during the process of examining the data. The procedures used are either dependent on the frequency of occurrence of something or adopt the process of 'scaling' to decide on the data to be included. Scaling requires grouping the data as 'important' or 'not-important', with the latter being deleted. However, the basis for the classification is seldom made clear, and there is a risk that scaling will result in loss of the 'richness' of the data, so the researcher must have clear reasons why informal methods are being used.

4.7.2.2 Formal Methods

These are associated with the positivistic paradigm and include content analysis and repertory grid techniques:

Content Analysis

This is a method of systematically changing text to numerical values suitable for quantitative data analysis techniques. The process involves examining a document, including audio or video material, and classifying the contents into predetermined coding units. The main steps of the analysis are sampling and constructing a coding frame. Depending on the volume of the material, a sampling rationale must be determined as to how much of the material to include in the analysis. The coding structure must then be determined, which includes certain phrases, words or themes, and the analysis is based on the frequency of occurrence (Collis and Hussey, 2009).

Repertory Grid Technique

Collis and Hussey (2009) describe the repertory grid technique as one of the formal methods of analysing qualitative data and ‘personal construct theory’ as the basis for this technique. This technique allows the interviewer to get a “mental map” of the way the interviewee sees the world and to note the picture with minimum bias. The technique is therefore a “framework of patterning” of individual experience in order to turn the data into a format where statistical analysis could be used. The method is used in interviews where the researcher is unable to formulate appropriate questions and the interviewee has difficulty in clearly structuring his opinion.

4.7.2.3 Non-Quantifying Methods

Collis and Hussey (2009) assert that in phenomenological research generating qualitative data, it may not be practical or desirable to use quantifying methods of analysis. The researcher must become very familiar with the data collected,manage the data effectively, and adopt the most suitable method, among the many non-quantifying methods, some of which are reviewed in the following sections (Collis and Hussey, 2009).

The General Analytical Procedure

The General Analytical Procedure, described by Miles and Huberman (1994), is based on sorting, collating, referencing, coding and categorising the data according to identified patterns and themes, and then summarising the findings and using the summaries to create generalisations.

In describing the General Analytical Procedure method, Miles and Huberman (1994) define qualitative data analysis as comprising three simultaneous lines of activity: data reduction, data display, and conclusion drawing and verification.

Data reduction of written field notes or interview transcriptions involves selecting, focusing, simplifying, abstracting, and transforming the data, and is a continuous process throughout the progress of the research. Data reduction, as a form of data analysis, has also been described as data condensation since it entails sharpening, sorting, concentrating, discarding and organising data, using methods such as selection, summarising, paraphrasing and pattern recognition, such that final conclusions can ultimately be drawn and verified (Miles and Huberman, 1994).

Data display is described as an ordered and condensed assembly of information that helps the viewer to understand what is taking place, draw conclusions and take action. The most common form of data display is extended text but this is considered cumbersome and poses the risk of the researcher drawing hasty and unfounded conclusions. Better and more practical display methods include different types of matrices, graphs, charts and networks, designed to organise and present information into readily accessible and compact forms that allow the analyst to either draw conclusions or progress to further data analysis stages (Miles and Huberman, 1994).

The third line of activity in this method of analysis is the conclusion drawing and verification stage. This stream in fact starts from the data collection stage when the researcher starts to decide where different data fit and what they mean, noting patterns, formulating explanations and gathering evidence, in a broad manner initially while maintaining openness. As the analysis progresses, these initial conclusion constructs become more explicit and well based, although 'final' conclusions are not usually compiled until after the data collection and data analysis are complete (Miles and Huberman, 1994).

Conclusion drawing is only part of the process of formulating final conclusions based on the qualitative data analysis, and conclusion verification needs to be continuously carried out as the analysis proceeds. The conclusion verification involves the researcher frequently revisiting the original transcripts or field notes, or through organised reviews amongst colleagues, to put together a consensus of the derived conclusions (Miles and Huberman, 1994).

Additionally, Collis and Hussey (2009) refer to Miles and Huberman (1994) and describe the General Analytical Procedure method for analysing qualitative data as being particularly appropriate where a large volume of data has been generated, in a managed and controlled environment and with systematic rigour. The method is based on "coding, summarising, categorising and identifying patterns and themes".

The General Analytical Procedure, according to Collins and Hussey (2009) involves the following steps:

- Convert rough field notes into clear written records;
- Ensure that material from different sources or data collection methods is properly referenced;
- Allocate an appropriate specific code to each element as early as possible to facilitate identification;
- Group codes into smaller categories in respect of emerging patterns or themes;
- Write summaries of findings at different stages, which will help identify shortfalls in the data;
- Use summaries to create generalisations to test existing theories or form new ones; and
- Repeat the process until confidence is developed that the generalisations are able to withstand analysis under the existing theories, or develop new ones.

Cognitive Mapping

Collis and Hussey (2009) describe cognitive mapping as an analysis method which is used to "structure, analyse and make sense of written verbal accounts". They refer to Kelly (1955) and his 'personal construct theory' as the basis for this technique. They also cite Ackermann et al. (1990) who explained the personal construct theory on the basis of the "predict-and-control view of problem solving" in that people try to understand the world in order to predict what might happen in the future, and then take appropriate action to attempt to achieve the desired outcome of the future within that world. The method extends the use of this theory further than the repertory grid techniques to give a powerful interviewing tool for taking notes during an interview or to record transcripts of documentary data such that later analysis is possible (Collis and Hussey, 2009).

The technique is used for projects concerned with developing strategy but also used in action research. There are cognitive mapping software packages available, which can be used to build models and analyse qualitative data while retaining the meaning of the original field data (Collis and Hussey, 2009).

Data Displays

Although the Data Displays method is considered by Miles and Huberman (1994) as one of the components of the General Analytical Procedure method, Collis and Hussey (2009) categorise Data Displays as an independent non-quantifying method in its own right. Collis and Hussey (2009), however, refer to the work of Miles and Huberman (1994) who prepared an extensive guide into the use of data display techniques, such as networks, matrices, charts and graphs for analysing qualitative data. A display is defined as a systematic visual presentation of information in order to derive valid conclusions and take appropriate action. Some of the data display suggestions for this method are presented below:

- Networks: these are a set of points linked with lines to illustrate existing associations between them, such as organisational charts.
- Matrices: these comprise rows and columns with appropriate headings, similar to computer spreadsheets. They can take different formats ranging from simple matrices resembling check lists to complex matrices.
- Event flow networks: used for displaying complex relationships, sequences or events, and can be the starting point for an eventual ‘causal analysis’ (which event led to which).
- Effect matrices: used to represent and display the effect on the state of individuals, relationships, groups or organisations following the implementation of a change. The change can be displayed sequentially with different aspects displayed separately.

The analysis process starts with the researcher becoming familiar with the data, constructing the appropriate displays and finally deriving conclusions.

Grounded Theory

According to Collis and Hussey (2009), Grounded Theory, which was originally conceived in the medical field, is now used in business research and is helpful in analysing qualitative data where there is no predefined theoretical structure. The method is explained by the following coding stages (Collis and Hussey, 2009):

- Open coding, which is the basic level of coding using simple codes to aid theory development, by identifying and sorting the data into recognisable categories with predefined properties along a continuum.
- Axial coding, which is extended from the open coding stage and involves grouping categories and sub-categories together, by restructuring the data to reveal links and relationships. This is the stage where mini theories are developed about relationships which still need to be verified.
- Selective coding, which involves selecting the main category, relating it to other categories and validating the relationships. Themes, are developed in this stage, which are then `grounded' with reference back to the original data.

Quasi-Judicial Method

Collis and Hussey (2009) explained this method, which is derived from legal processes and involves using judicious style argument to interpret empirical evidence, which is data based on experience or observation. In this method data are continually analysed, during which time the researcher must keep focused on matters such as the issues being researched, other relevant evidence available, other means of understanding the data and the data collection methods used.

This method therefore relates to the character and quality of the data and the case it supports, with emphasis being placed on continually assessing the evidence (data collected) in search of relevant explanations (Collis and Hussey, 2009).

4.8 Research Design for this Research

The major focus of the research is on developing a GIS-based model to aid decision making in pavement maintenance management, thus requiring more quantitative data collection and analysis techniques than qualitative data, so this inclines the research towards the positivistic side of the spectrum for this aspect of the research. Therefore, this research represents a positivism philosophy.

In addition, Jankowicz (2005) guides that when starting research a researcher should follow three main steps with regard to selecting research methodology (Jankowicz, 2005):

- Select the most appropriate research method (strategy according to the model adopted by Denscombe (1998);
- Decide on one or more suitable techniques (methods) to elicit the data from the participants; and
- Analyse the data rigorously to identify meanings from the data obtained.

Jones (2004), who reasoned that there is not a principled difference that separates the two broad research paradigms, and that many of the criticisms made about one technique could be equally applied to the other, also supports this approach. For practical research purposes, he argued, there is not an automatic preference for one technique above another, but that it would rather depend largely on the purpose of the study which technique was most appropriate (Jones, 2004).

According to Johnson and Onwuegbuzie (2004), in order to implement mixed research methods in an effective manner, researchers must first consider the relevant qualities of quantitative and qualitative research. The most important characteristics of traditional quantitative research are a focus on deduction, confirmation, theory/hypothesis testing, explanation, prediction, standardised data collection, and statistical analysis; while the major characteristics of traditional qualitative research are induction, discovery, exploration, theory/hypothesis generation, with the researcher being the main "instrument" of data collection, and qualitative analysis. This course of action will enable the research to benefit from the strengths and avoid the weaknesses of both the quantitative and the qualitative research methods (Johnson and Onwuegbuzie, 2004).

The conducted research starts with reviewing the literature to identify factors affecting pavement maintenance prioritisation, where these factors are to be rated in terms of their importance by professionals from different local authorities. Furthermore, interviews are to be conducted with experts in the field to justify the rated factors. However, the main aim of this research is to develop a model that is applicable for a local authority, with the expectations for it to be applicable for similar local authorities. Hence, the adopted research approach for this research is abduction.

4.8.1 Selection of Methodological Choice, Strategy and Time Horizon

Johnson and Onwuegbuzie (2004) furthermore concluded that mixed methods research offers great promise for practicing researchers who aspire to see methodologists describe and develop techniques that are closer to what they actually use in practice. Mixed methods research can also help bridge the rift between quantitative and qualitative research. Methodological work on the mixed methods research has been widely seen in recent years; however, a lot of work remains to be undertaken in the area of mixed methods research especially regarding its philosophical position, designs, data analysis, validity strategies, mixing and integration procedures, and rationales (Johnson and Onwuegbuzie, 2004).

The adopted methodological choice for this research is the mixed method in order to achieve the aim of research. The reason for that is using questionnaire and interview techniques to obtain quantitative and qualitative data respectively.

Embarking on a mixed method research, the main research activities will be centred on the following three strategies:

1. Surveys based on the two elements of a questionnaire and interviews, to obtain both qualitative and quantitative data
2. GIS-based modelling to develop decision support aid
3. Case study to test the model

The adopted time horizon for this research is cross-sectional. The reason for that is the researcher requires investigating and working on multi-tasks such as reviewing literature, collecting data and developing the model over the same period.

4.8.2 Data Collection and Data Analysis

Regarding data collection methods in a mixed methods research environment, Johnson and Onwuegbuzie (2004) defined the "fundamental principle of mixed research" as the researcher's ability to collect multiple data using different strategies, approaches, and methods in such a way that the resulting mixture or combination is likely to result in harmonising strengths and non-overlapping weaknesses. Johnson and Onwuegbuzie (2004) therefore maintained that effective use of this principle is a major source of validation for using mixed methods research because the result will be superior to single method research (Johnson and Onwuegbuzie, 2004).

The detailed data collection methods for this research therefore are as follows:

- Questionnaire survey to establish the most significant factors affecting pavement maintenance management decisions;
- Interviews with experts from different local authorities to justify the rated factors; and
- case study data within the Surrey County Council to test the model

4.8.2.1 Data for Factors Affecting Pavement Maintenance Priority Rating – Questionnaire

Appendix A shows the survey questions employed in the pavement maintenance prioritisation survey questionnaire, which was undertaken during the survey phase of the research. The questionnaire survey was directed at practicing professionals in local road authorities, for the purposes of obtaining a reliable consensus on the most significant factors influencing pavement maintenance management decisions in local authorities at present; and establishing the relative weight assigned to such factors by different experts. These factors were eventually justified and used in the development of the GIS-based model to aid the multi-criteria decision making process in pavement maintenance management.

The questionnaire was disseminated to the target survey participants by e-mail, and the responses were then analysed to extract the most significant factors agreed upon. Chapter Five of this thesis presents the questionnaire survey responses and analysis of the results; Chapter Six presents the conceptual model; and Chapter Seven details the GIS-based model development and testing phase.

4.8.2.2 Data for Rated Factors Justification - Interviews

Appendix D contains details of the interview questions adopted for the interviews. A total of four interviews were conducted with experts from different local authorities. The purpose of the interviews was to justify the rated factors in the questionnaire.

4.8.2.3 Case Study: Surrey County Council

The case study approach has been selected as one of the research strategy components for this research. The case study of Runnymede District within the Surrey County Council is used to test the proposed model. This will help to check that it can be used and applied within similar local road authorities**.**

4.8.3 Data Analysis Techniques Adopted

As established previously in this section, this research is based on a mixed methods approach, which involves both qualitative and quantitative methodologies. Therefore, the approach to be adopted for analysing the data must also comprise a combination of appropriate methods to suite each type of data.

Data from the questionnaires generated lists of pavement maintenance management factors rated by the respondents according to their significance. These data are quantitative in that they have a numerical aspect in terms of ranks or weights.

For the questionnaire survey therefore, basic statistical methods were adopted to calculate the average scores of the questionnaire outcomes. In this study, to test the reliability of the outcome of the questionnaire survey, SPSS (Statistical Package for the Social Sciences) was used for computing Cronbach's alpha to perform an internal consistency analysis for the responses to all the questions from the questionnaire (see Chapter Five for details).

Data from the interviews generated quantitative data in that they have a numerical aspect in terms of ranks or weights, and qualitative as they justify and describe the factors. In order to maintain external validity, experts in pavement maintenance are selected from different local road authorities to interview. Moreover, to ensure the suitability of measured parameters, interviews are used to examine the results from the questionnaire survey. Construct validity is maintained for this study, as both the questionnaire and interview findings show the same tendency.

Basic statistics is used for the collected data analysis, and Analytical Hierarchy Process (AHP) is used for specific calculations. Details of the data analysis can be found in Chapter Five.

Figure 4.2 below illustrates diagrammatically the adopted research design model for this research.

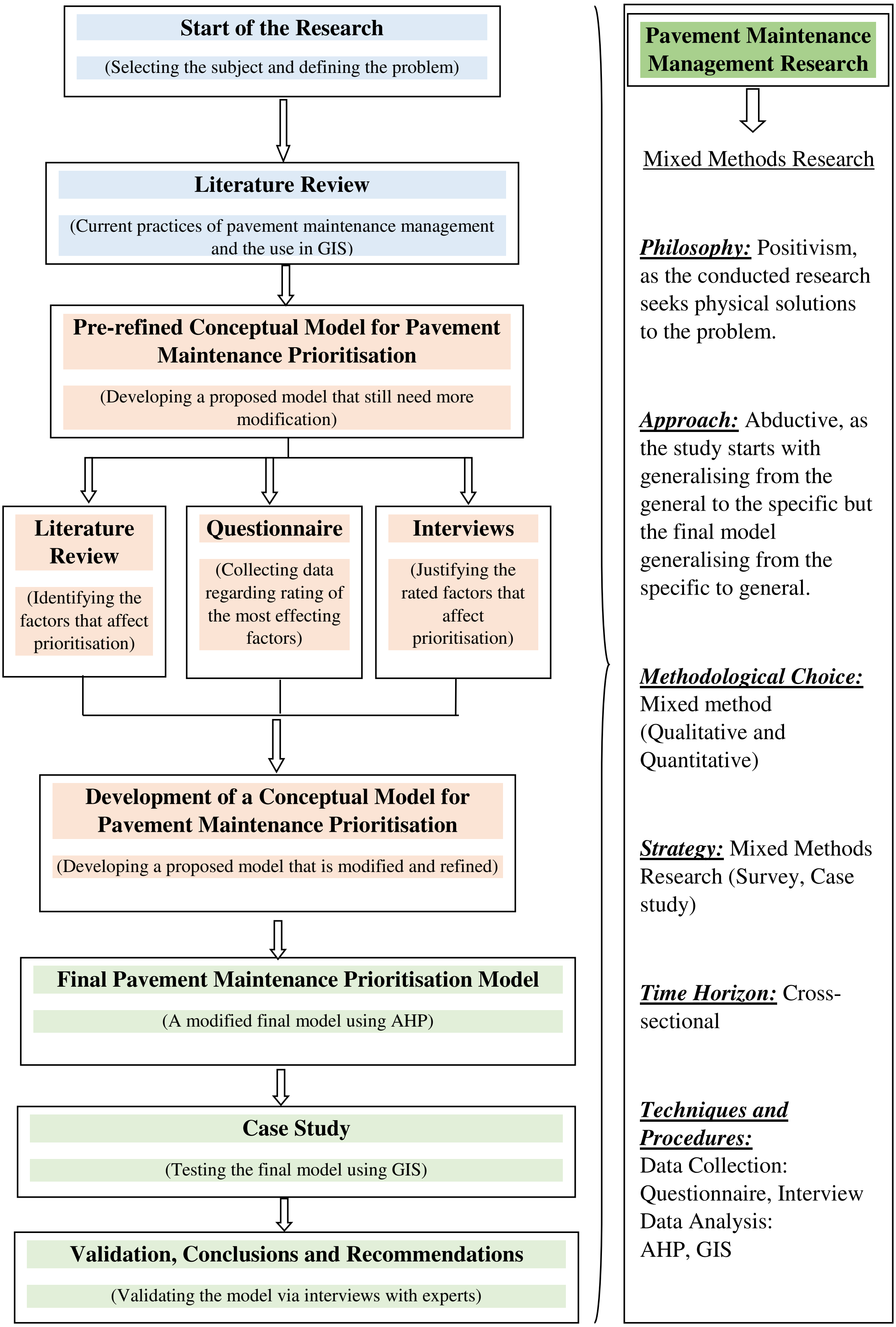


Figure 4.2: Research Design Model

4.9 Research Limitations

Every research has limitations arising firstly from the defined scope of research and the specified research aim and objectives; secondly from the research design adopted which comprises the data collection and analysis techniques; and finally from the interpretation of the results and other issues that need to be considered when trying to generalise these results to wider areas of interest.

Chapter Nine of this thesis addresses the limitations affecting this research based on each research component in turn.

Chapter Five

Impacting Factors of Pavement Maintenance via Questionnaire Based Survey

5.1 Introduction

One of the main data collection methods adopted in this research is the survey questionnaire; the other being the local road authority interviews. A thorough review of literature is performed in order to identify and account for the factors influencing pavement maintenance prioritisation decisions, and a well-grounded justification for the questionnaire is provided. Subsequent to carrying out the survey and collecting the responses thereof, an analysis of the results is performed employing the Analytical Hierarchy Process (AHP) method. Likewise, conducted interviews are evaluated to support and complement the data obtained through the survey questionnaire. Finally, considerations such as the validity and reliability of the survey are also dealt with.

The aim of the survey was to establish a general consensus amongst Local Road practicing professional road engineers and managers, as to the most significant factors affecting pavement maintenance management prioritisation decisions. The draft questionnaire was designed after identifying 14 factors affecting prioritisation decisions, and was subsequently modified and refined based on the outcome of the pilot survey discussed below, before being delivered to the finally selected target participants for the proposed main survey. The final version of the adopted survey questionnaire is included in Appendix A.

5.2 Pilot Survey

An important preparation step in questionnaire surveys is to carry out a limited pilot survey to test the questionnaire on a small sample of subjects first before disseminating the main survey. In this research, the researcher used a pilot survey to seek feedback from six professionals, from different local road authorities, many of whom have extensive pavement maintenance experience. The target survey participants were selected based on their experience, availability and readiness to take part in the research.

The primary aims of the pilot survey were to test the effectiveness of the questionnaire design and detect any flaws in the questionnaire details, in order to modify the survey design, based on the feedback, prior to the main survey. The principal objective of this exercise was to ultimately maximise the response rate of the main survey and reduce the risk of inaccuracies in the answers given.

The pilot survey therefore included a feedback questionnaire, which was designed to test the efficiency of the technique and contents of the survey, examine the adequacy of the questions in covering the intended topic, check question clarity and ascertain the length of time taken by each participant to complete the questions. The pilot survey also sought and received many constructive comments, which enabled the questions to be refined before the main survey. Two PhD postgraduate researchers from the University of Manchester and three professionals and specialists in pavement maintenance from different local road authorities participated and responded to the pilot survey, where the response rate was 100%. Appendix B of this thesis contains the adopted pilot survey questionnaire.

5.3 Selection of Target Recipients of the Main Survey

According to Bell (1999), depending on the size of the survey and the target population, the researcher may need to employ sampling techniques to be able to produce a sample, which should be representative of the population as a whole, and be able to draw generalisations from the findings.

The task regarding the questionnaire survey was therefore deciding on the survey participants' sample from amongst the numerous local authority road managers. The objective was to include road authority representatives from the Shire counties, the Metropolitan authorities and the Unitary Councils, representing different UK regions.

A total of 195 survey questionnaires were sent out to road managers representing most of the local road authorities in the UK. Figure 5.1 is a UK map showing the counties covered by the questionnaire survey.

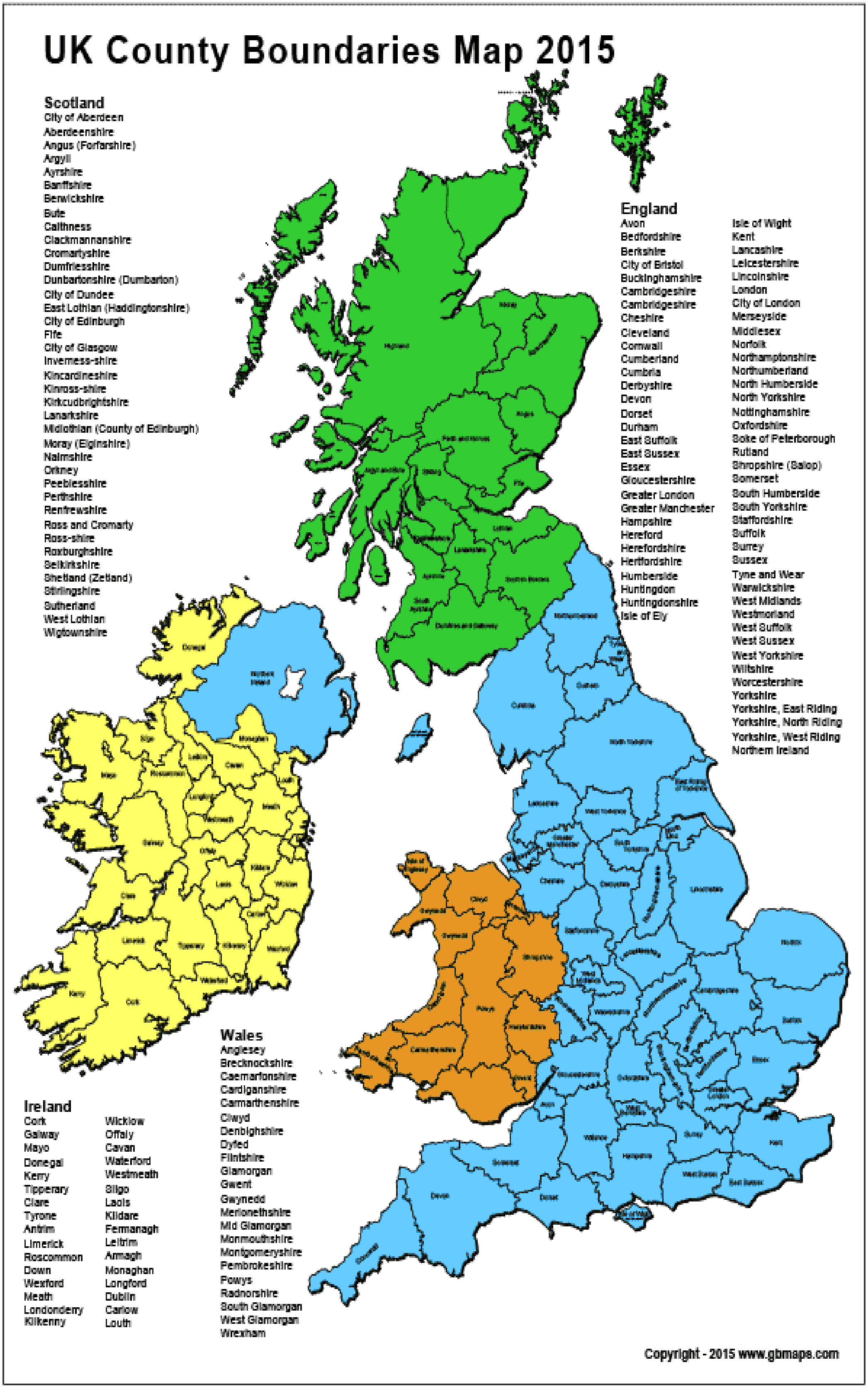


Figure 5.1: UK Counties Covered by the Questionnaire. Source: GBMAPS (2015)

5.4 Method of Distribution of the Main Survey

The questionnaire format was set to Microsoft Word and sent as an attachment to e-mails. However, taking into account the generally acknowledged low response rate of questionnaires, reminders were sent out to non-responding recipients after approximately five weeks of the original consultation date. Appendix C presents the full list of local authorities consulted by the questionnaire survey and those that responded.

5.5 Response Rate

Initially, the response rate was low; however, the response improved dramatically following the "reminders" stage of the survey, and the ultimate number of completed questionnaires received by the researcher was 67 responses, which amount to 34% response rate. The covering letter to the questionnaire gave details of the purpose of the survey being part of a study conducted into pavement maintenance management, and the prioritisation of pavement maintenance. Also, it presented the objectives of this part of the research including verifying the most significant criteria used in prioritising pavement maintenance, and developing a GIS-based model to enhance the prioritisation decisions of pavement maintenance.

Figure 5.2 is a Pie-Chart showing the response rate with the responses split between first attempt responses and those that followed the reminder.

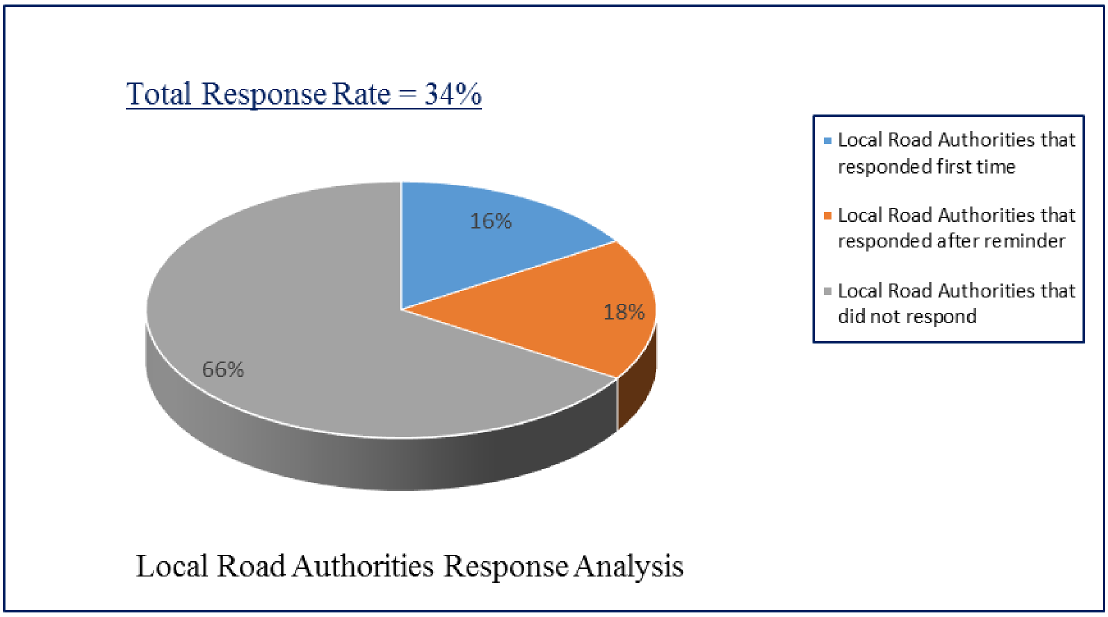


Figure 5.2: Local Road Authorities Survey Response Analysis

5.6 Factors Affecting Pavement Maintenance prioritisation Decisions

A total of 14 factors were included by the researcher in the questionnaire survey for prioritisation decisions in road maintenance schemes. The objective was for the respondents to rate these factors according to the degree of importance based on the Likert Scale of the following well-defined, evenly spaced rating range continuum:

1 = Not Important
2 = Less Important
3 = Important
4 = Very Important
5 = Extremely Important

The factors included in the survey were based on the literature review, discussions with professionals and on the experience of the researcher, and these are presented in Table 5.1 below:

No.	Factor
1	Remaining Service Life
2	Road Condition Indicator (RCI)
3	Type of Deterioration
4	Observed Deterioration Rate
5	Traffic Diversion
6	Importance of Road/Classification
7	Annual Average Daily Traffic (AADT)
8	Possible Conflict or Overlap with Other Road Works
9	Risk of failure
10	Safety Concern
11	Accident Rate (related to surface condition)
12	Scheme Cost
13	Available Budget/Funding
14	Whole Life-Cycle Cost

Table 5.1: Pavement Maintenance Prioritisation Factors included in the Survey

5.7 Survey Results

Table 5.2 below shows the breakdown of responses of questionnaire conducted in local road authorities. In the stated table, factors are shown as F1, F2... F14 to represent the factors as shown below:

F1: Remaining service life

F2: Road Condition Indicator RCI

F3: Type of Deterioration

F4: Observed Deterioration Rate

F5: Traffic Diversion

F6 Importance/Classification of the Road

F7: Average Daily Traffic ADT

F8: Possible Conflict or Overlap with Other Road Works

F9: Risk of Failure

F10: Safety Concern

F11: Accident Rate (related to surface condition)

F12: Scheme Cost

F13: Available Budget/Funding

F14: Whole Life-Cycle Cost

Factors	Rating Scores					Total Responses	Total Scores $\sum$	Mean $\bar{x}$	Rank
	1	2	3	4	5				
F1	2	1	15	16	33	67	278	4.15	4
F2	1	4	14	32	16	67	259	3.87	8
F3	1	3	14	32	17	67	262	3.91	6
F4	2	5	16	23	21	67	257	3.84	9
F5	7	10	19	19	12	67	220	3.28	12
F6	0	0	12	29	26	67	282	4.21	3
F7	3	14	21	24	5	67	215	3.21	14
F8	2	4	22	22	17	67	249	3.72	11
F9	4	4	11	25	23	67	260	3.88	7
F10	2	1	7	21	36	67	289	4.31	2
F11	4	4	9	24	26	67	265	3.96	5
F12	4	11	23	21	8	67	219	3.27	13
F13	2	0	7	13	45	67	300	4.48	1
F14	2	7	16	22	20	67	252	3.76	10

Table 5.2 Breakdown of Responses of Questionnaire

The given Table 5.2 contains a summary of the factors ratings provided by 67 local road authorities' representatives. The scores are listed in order from 1 to 5 and are shown along with the total and mean values (rating values) for each factor. Factors are ranked according to the mean values of the factors in order to establish a pattern in the attitude of local road authorities to pavement maintenance management.

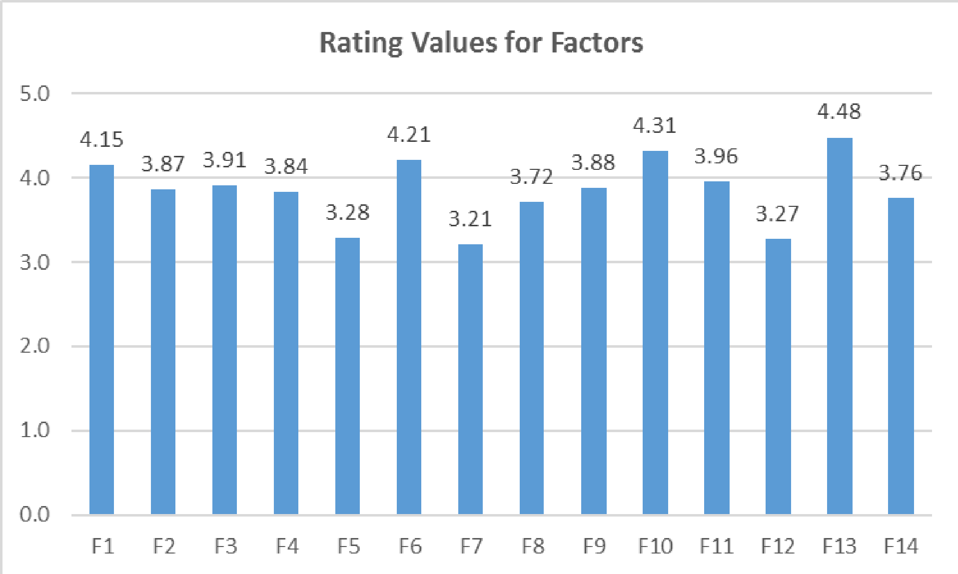


Figure 5.3: Rating Values for Factors

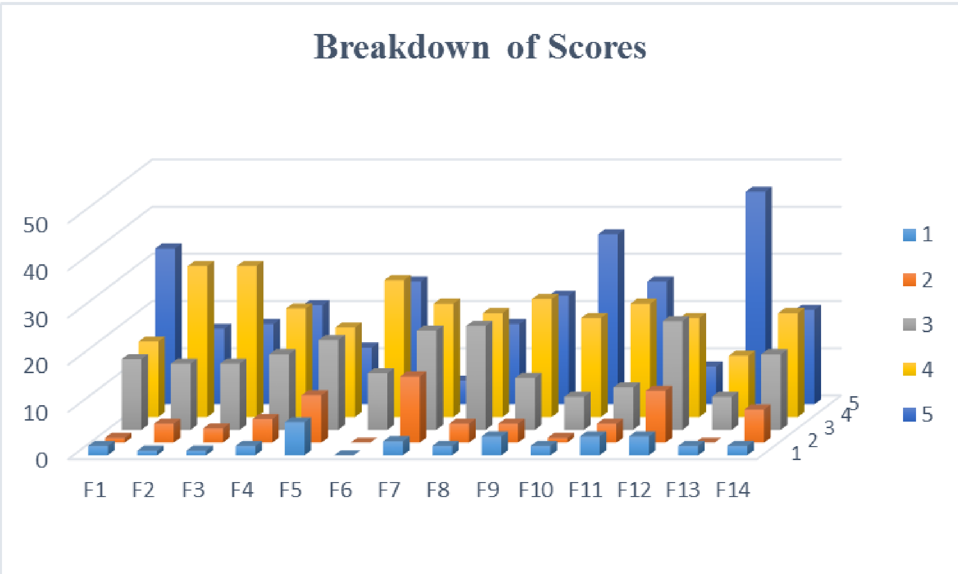


Figure 5.4: Breakdown of Scores

Figure 5.3 provides a graphic illustration of the factor rating scores, and Figure 5.4 shows the listing of scores in order. It is evident from the graphs that the highest rating factor value corresponds to Available Budget/Funding (F13) and the lowest rating score is achieved by Annual Average Daily Traffic AADT (F7).

5.8 Specialists' Views on Factors Affecting Pavement Maintenance

Interviews are conducted in order to reveal the underpinning reasons why survey participants rated the stated factors as they did (See Appendix D). In this section, interviews with specialists thematically relevant to the survey questionnaire are discussed. The method of selecting interviewees mirrors the procedure used for choosing the target participants in the survey. The total number of local road authority officials who have been interviewed is four.

Interviewees are requested to rate the factors and account for the motives behind their reasoning. The statements from the interviews are subsequently juxtaposed with the survey responses adopting the triangulation approach as a means of corroborating the questionnaire data. Interviews are presented in the following order: i) profile description of the interviewee, ii) factor rating along with the reason for it. Conclusions are made upon the completion of the interview process.

5.8.1 Interview with Specialist 1

Profile: The first specialist has 15 years of experience in highways and transportation as an Asset Manager at a local authority, and a member of the UK Road Board.

Factor	**Rating**	**Reason**
Remaining Service Life	4	This is a very important factor. SCANNER identifies the surface condition. The underlying structural condition is measured by 'Deflectograph', but this is an expensive survey which is reliant on other data sets which may not be readily available. SCANNER treatments are used, but this does not give an indication of the remaining life, just the severity of deterioration.

Road Condition Indicator RCI	4	This is the national statistical indicator for A, B, C road classification and we use it to report to our members to monitor condition. However, it is recognised that a worst first approach i.e. just targeting 'red' is not the best asset management approach. The use of intermediate treatments targeting amber and some red is preferred.
Type of Deterioration	4	Informs (1) Nature of repair treatment (2) Intervention point
Observed Deterioration Rate	4	Informs (1) Short-term cost implications of necessary reactive repairs (2) Change point between intermediate surface treatments and longer term. More expensive resurfacing repairs. The sweet spot for intervention should be as close to the latest opportunity before stepping up to the next level of treatment as possible.
Traffic Diversion	3	Traffic diversion could increase the journey length and the cost could increase as well.
Importance/Classification of Road	4	Road Classification and Road Hierarchy indicate the importance of a road.
Annual Average Daily Traffic (AADT)	4	Factor (1) Indicates actual use of road rather than importance (2) That helps determine treatment design and necessary pavement depth / strength.
Possible Conflict or Overlap with Other Road Works	2	This could stop a scheme being delivered but should not hinder the development of a 3-5 year forward programme as utilities seldom plan this far ahead.

Risk of Failure	3	It is covered by (1) Whether the road is part of the resilient network. It could be picked up in the importance of the road. (2) Observed Deterioration Rate (3) Type of Deterioration
Safety Concern	3	These should ideally be resolved by immediate response to mitigate danger by repairs or warning. For most scheme prioritisation, this would not be a significant factor. However, there may be exceptions that need to be identified or accelerated.
Accident Rate (related to surface condition)	3	Wording here ‘accident rate’ is important. RTA’s seldom have road condition as a contributory factor and driver behaviour / Aids to Movement are more important. The use of a coarse accident rate rather than certain specifics related to road condition is not appropriate as it can skew the results to prioritise sites where structural maintenance works will have no real benefit. i.e as causal issues are not addressed, there is no change in RTA’s.
Scheme Cost	3	Available funding determines the asset management strategy, treatment response and timing of repairs. Ideally, this would be measured in a matrix with Scheme efficiency so that an initial coarse cost vs. benefit could be identified.
Available Funding	5	Available funding is the ultimate criterion. Without funding nothing is possible. Available funding determines the asset management strategy, treatment response and

		timing of repairs.
Whole Life-cycle Cost	4	Ideally, this would be the highest priority if budget was no problem. However, it may be too heavy on initial capital cost, which may not be affordable. Treatments may have to be reduced or schemes delayed.

5.8.2 Interview with Specialist 2

Profile: The second specialist has 14 years of experience in highways network management as a Principal Engineer at a local authority, and a specialist in pavement assessment and maintenance.

Factor	**Rating**	**Reason**
Remaining Service Life	4	This factor partially determines the type of treatment that can be applied. We are obliged to concentrate as much resource as possible on lower cost preventative maintenance techniques.
Road Condition Indicator RCI	4	This is an important guidance but RCI data should be validated and investigated further. Some data can be misleading when detritus is present or similar issues.
Type of Deterioration	4	The type of deterioration may guide the appropriate form of treatment selection.
Observed Deterioration Rate	4	This information will typically only be available from the annual condition surveys. This is therefore of limited importance in site selection.
Traffic Diversion	3	This only has minor influence on prioritisation, unless a site’s exclusion would affect a whole route.
Importance/Classification of Road	4	Higher importance of roads involving route disruptions.
Annual Average Daily Traffic (AADT)	4	This will feature as a factor but it is not checked as a routine input.

Possible Conflict or Overlap with Other Road Works	4	Can only protect sites for 36 months from future disturbance by public utilities. So work is indeed coordinated but is still a relatively low factor.
Risk of Failure	4	Whilst funding is still available to a highway authority – roads will still be prioritised if there is an immediate risk of failure.
Safety Concern	4	If funding permits, these sites will always be treated as a matter of course.
Accident Rate (related to surface condition)	5	If accidents are attributable to a highway surface issue and evidenced as such by SCRIM, they will receive a high priority to avoid future litigation.
Scheme Cost	4	It is considered in prioritisation for programming a scheme before it deteriorates to a deeper form of construction.
Available Funding	5	Always a determining factor where indicative pavement maintenance funding remains at around a third of actual requirements.
Whole Life-cycle Cost	4	This would be the highest priority if sufficient funding was available to a highway authority to utilise asset management techniques.

5.8.3 Interview with Specialist 3

Profile: The third specialist has 18 years of experience in strategy development for highway assets, including asset management policy and prioritisation as an Asset Planning Manager at a local authority, and a member of the Road Condition Management Group.

Factor	**Rating**	**Reason**
Remaining Service Life	5	Local Authority Asset Management consider this perhaps the most fundamental piece of information required to manage a highway network effectively, albeit the most difficult piece to accurately obtain.
Road Condition Indicator	3	National RCI’s tend to only be a guide towards a

RCI		potential problem. Schemes for prioritisation from RCI results alone are not developed in this local authority, as they can be misleading. However, the survey data beneath the RCI can be much more useful, i.e. cracking, rutting, profile, texture etc.
Type of Deterioration	4	The big gap between RCI/ machine survey data and site survey/ inspection/ testing is to more accurately ascertain the type of deterioration. Similar to Remaining Service Life above, knowing the reasons for deterioration is fundamental information in the process of major maintenance intervention and repair.
Observed Deterioration Rate	4	As for Type of Deterioration above, any information that assists in more accurately predicting the remaining service life is fundamental to the process of highway asset management
Traffic Diversion	3	The local authority highway network is compact when compared to the nature of other County sized authorities. Hence, there is limited variation in maintenance impact directly due to traffic diversion.
Importance/Classification of Road	4	The importance and typical use of the road is a very important factor when prioritising major maintenance works, in order to make sure the critical routes in the Borough remain serviceable. Borough is currently in the process of defining the 'resilient network', i.e. the critical part of the network that should take priority in an emergency, which will ultimately elevate the priority for maintenance for these routes.

Annual Average Daily Traffic (AADT)	2	Whilst the CV/lane/day is an important factor in maintenance prioritisation, overall AADT is less significant.
Possible Conflict or Overlap with Other Road Works	3	The aim of the local authority Asset Management is to maximise the life of any treatment on the network. One of our main ways to achieve this is to ensure that we co-ordinate with other roadworks (inc. utilities) so that any maintenance proposal is the final process on a stretch of road for many years to come.
Risk of Failure	4	Similar to Remaining Service Life and Type & Rate of Deterioration comments, ascertaining the level of risk of potential failure of a pavement to the Borough and the highway user is one of the main focuses of local authority Asset Management.
Safety Concern	5	The borough routine maintenance teams (i.e. not the borough Asset Management) are responsible for the day-to-day maintenance of the highway, and hence safety inspections and repair. In theory, there should be limited instances of major investment required primarily to address highway safety concerns.
Accident Rate (related to surface condition)	1	Whilst the Borough's skidding resistance policy involves an analysis of wet skidding accidents (and the prioritisation of schemes accordingly within overall maintenance priorities), accident analysis and prevention policy is not initially linked to pavement maintenance. There may be many more causes of accidents such as poor carriageway alignment, excessive speed etc. that would not initially be a maintenance related concern. The borough routine maintenance teams

		(i.e. not the borough Asset Management) are currently responsible for the day-to-day maintenance of the highway, and hence safety inspections and repair.
Scheme Cost	3	The borough (like most, if not all LHA's in England) are massively underfunded when comparing typical capital and revenue funding allocations with life-cycle cost model requirements. Whilst there will always be a compromise between what is needed and what is affordable, whole life cost is considered a much more important factor than individual scheme cost.
Available Funding	5	As mentioned above, the gap between available funding and steady state network condition funding continues to widen year on year, hence available funding is impacting on the ability to efficiently maintain the borough's highway network.
Whole Life-cycle Cost	5	For the borough Asset Management, this remains the fundamental financial consideration and maintenance driver when proposing capital investments in the highway network. However, in the political world, this is constantly being compromised with the pressure of the borough needing be seen to be doing more work on the ground, rather than solutions appropriate for minimising lifecycle costs.

5.8.4 Interview with Specialist 4

Profile: The fourth specialist has 24 years of experience in GIS development and data management as a GIS and data manager at a local authority, and 8 years of experience in road management as a consultant in the private sector.

Factor	**Rating**	**Reason**
Remaining Service Life	3	Determines treatment type and is an important factor when the age of road since the last treatment is known or accurately predicted.
Road Condition Indicator RCI	3	This is the national indicator and it is a good guidance but needs to be associated with other condition indicators.
Type of Deterioration	4	This is also the same as remaining service life would help to select the appropriate treatment and it is an important guidance.
Observed Deterioration Rate	3	This is important as it refers to the importance of the time of intervention. If pavement is repaired at the right time, it will be cost effective.
Traffic Diversion	4	Traffic diversion is considered important as it would affect the cost and community if it was needed.
Importance/Classification of Road	5	Classification of roads reflects the importance of the road, where major roads that link between areas are very effective in terms of repairs priority.
Annual Average Daily Traffic (AADT)	2	This is of less importance amongst other criteria since it is difficult to get accurate figures.
Possible Conflict or Overlap with Other Road Works	4	Coordination with other road works is important when planning repairs.
Risk of Failure	4	Risk of failure is an important criterion and it is linked to the condition of pavement.
Safety Concern	5	Ensuring safety is highly important in any planned repairs.
Accident Rate (related to surface condition)	4	This is important when accurate information is obtained and recorded that is related to the condition of pavement.

Scheme Cost	3	This is of less importance than the available funding and whole life cost.
Available Funding	4	Local authorities suffer from underfunding and try to strike a balance between cost and level of repairs.
Whole Life-cycle Cost	4	This is important for the asset management but again, underfunding is a barrier to planning treatments with consideration of whole life cost.

5.8.5 General Interviews Evaluation

Producing summaries of the interview scripts reveals slight divergence in personal views. The subjective perception is justified given the interviewees' different background and experience in pavement maintenance management within different local authorities. The slight differences in the factor ratings do not amount to incongruity. There is reasonable consistency in interviewees' opinions within contextual specifics, which leads to establishing a trend. Hence, it can be said that this research method produced thorough understanding of the assessment of factors through the numerical values attached to them.

To sum up, the Available Funding factor is agreed to be the most important factor related to pavement maintenance management, while the Annual Average Daily Traffic is ranked the least significant factor that affects pavement maintenance prioritisation.

Table 5.3 shows the mean scores from the interviews, and Figure 5.5 provides a graphic illustration thereof. As already stated above, factors are ranked for the purpose of corroborating the questionnaire survey results and trends by juxtaposing them against the interview findings within the framework of the triangulation approach. Only a slight variation between the interview and the questionnaire findings is evident, which has already been accounted for.

Factors	Ranking Scores					Total Responses	Total Scores $\sum$	Mean $\bar{x}$	Rank
	1	2	3	4	5				
F1	0	0	1	2	1	4	16	4.00	3
F2	0	0	2	2	0	4	14	3.50	5
F3	0	0	0	4	0	4	16	4.00	3
F4	0	0	1	3	0	4	15	3.75	4
F5	0	0	3	1	0	4	12	3.25	6
F6	0	0	0	3	1	4	17	4.25	2
F7	0	2	0	2	0	4	12	3.00	7
F8	0	1	1	2	0	4	13	3.25	6
F9	0	0	1	3	0	4	15	3.75	4
F10	0	0	1	1	2	4	17	4.25	2
F11	1	0	1	1	1	4	13	3.25	6
F12	0	0	3	1	0	4	13	3.25	6
F13	0	0	0	1	3	4	19	4.75	1
F14	0	0	0	3	1	4	17	4.25	2

Table 5.3: Average Scores of Interviews Outcome

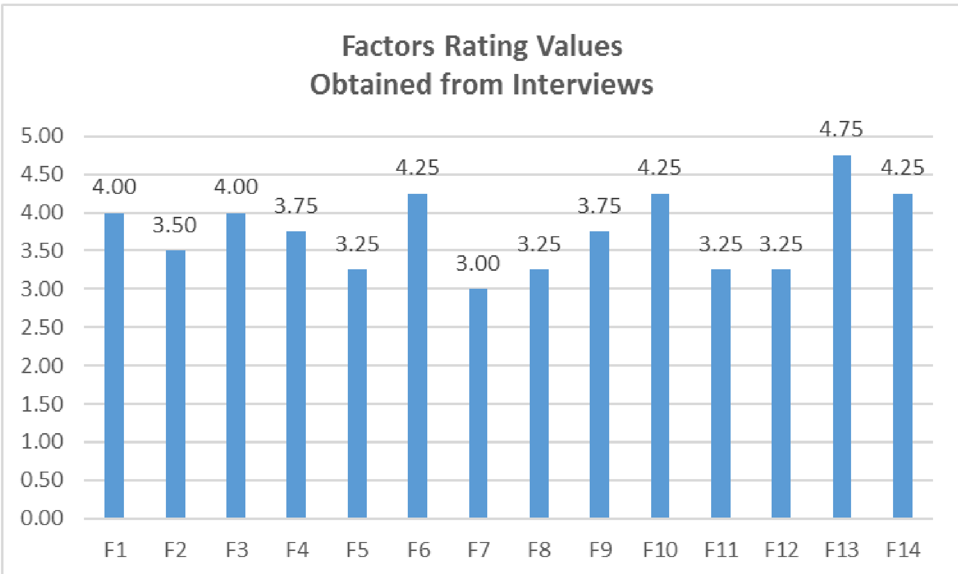


Figure 5.5: Factors Rating Values Obtained from Interviews

Table 5.4 below illustrates the comparison between findings from questionnaire and interview surveys. The Available Funding factor is agreed to be the most important factor related to pavement maintenance management, while the Annual Average Daily Traffic is ranked the least significant factor that affects pavement maintenance prioritisation. Only a slight variation between the interview and the questionnaire findings is evident, which has already been accounted for.

Factors	Ranking from Questionnaire	Ranking from Interviews
F1	4	3
F2	8	5
F3	6	3
F4	9	4
F5	12	6
F6	3	2
F7	14	7
F8	11	6
F9	7	4
F10	2	2
F11	5	6
F12	13	6
F13	1	1
F14	10	2

Table 5.4: Comparison between Findings from Questionnaire and Interview Surveys

5.9 Reliability and Validity of the Analysis of Survey Results

Evaluating the quality of the survey and establishing trustworthy findings are achieved via testing the reliability and validity of the survey findings (Robson, 2011; Zohrabi, 2013). There is a relation between reliability and validity, however, if a questionnaire is valid, that does not mean it is always reliable (Neuman, 2003; Saunders et al., 2012).

Figure 5.6 below illustrates the stages of a question’s test for its validity and reliability:

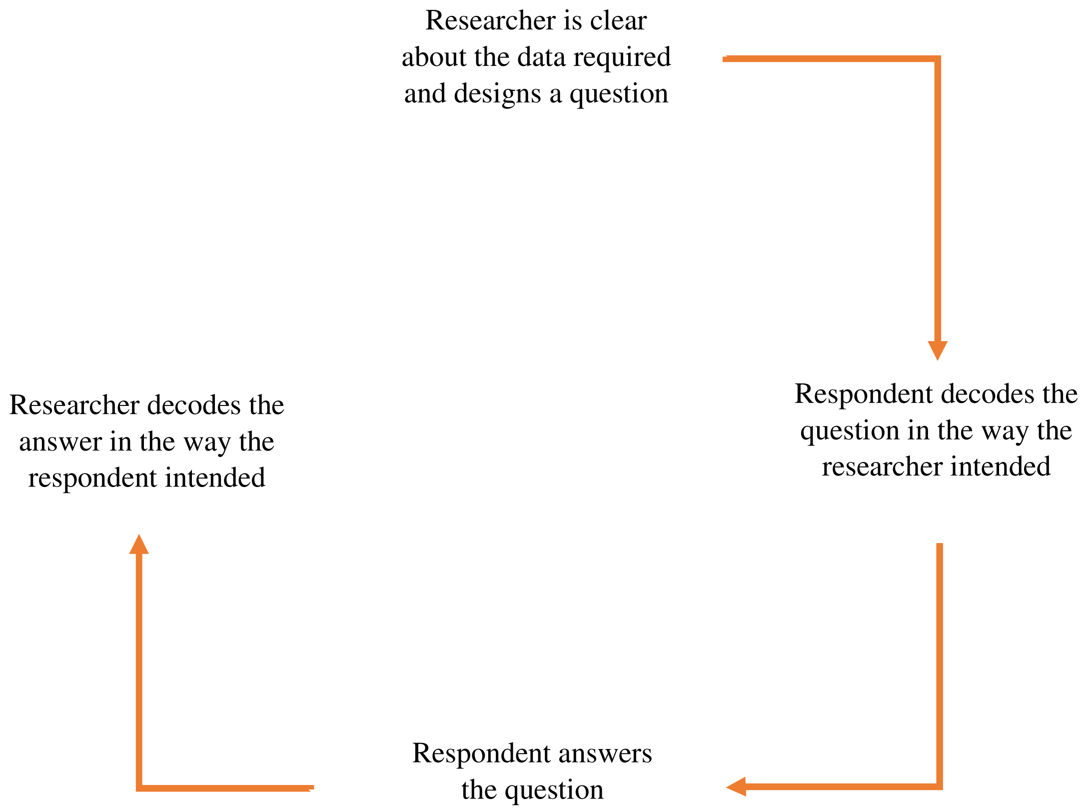


Figure 5.6: The stages for a question to be valid and reliable. (Saunders et al., 2012)

Reliability is concerned with consistency of the findings obtained from given research (Collis and Hussey, 2009; Robson, 2011; Saunders et al., 2012; Zohrabi, 2013). In order to assess the reliability, three common approaches are outlined (Saunders et. al., 2012 cited Mitchell, 1996):

- Test re-test approach;
- Alternative form Approach;
- Internal consistency approach.

Test re-test and alternative form approaches have major limitations such as requiring the questionnaire to be completed twice by participants, which could create problems, or requiring two alternative forms of the same questions, which is difficult to ensure the questions are substantially equivalent (Saunders et al., 2012). That made internal consistency approach a useful form of reliability assessment. Hence, the internal consistency approach is adopted for this study.

The internal consistency approach measures the consistency of responses across all the questions from the questionnaire by calculating a reliability coefficient called Cronbach's alpha (Saunders et. al., 2012). In this study, SPSS (Statistical Package for the Social Sciences) was used for computing Cronbach's alpha to perform an internal consistency analysis for the responses to all the questions from the questionnaire. Appendix E shows the calculations of Cronbach's alpha in SPSS.

Cronbach's alpha values vary between 0 and 1, where values of 0.7 and above indicate that the questions combined in the scale are measuring the same thing (Saunders et. al., 2012). However, when the value of Cronbach's alpha is less than 0.7, the reliability can be increased by removing an item or more from the questionnaire. The analysis was performed for all questions, and the values of Cronbach's alpha were greater than 0.7. This indicates that the responses for all questions have internal consistency; therefore, the results from the analysis have internal consistency, and are thus reliable.

Furthermore, the interviews with specialists in pavement maintenance management indicate similar outcomes. Therefore, reliability is obtained for the questionnaire survey.

Table 5.5 summarises the results of the performed reliability analysis in SPSS.

Items Included in the Questionnaire	Original Cronbach's Alpha Value	Items for Deletion	Cronbach's Alpha Value if Item Deleted
Remaining Service Life	0.740	_	0.740
Road Condition Indicator (RCI)		_	0.740
Type of Deterioration		_	0.706
Observed Deterioration Rate		_	0.729
Traffic Diversion		_	0.726
Importance/Classification of Road		_	0.725
Annual Average Daily Traffic (ADDT)		_	0.718
Possible Conflict or Overlap with Other Road Works		_	0.729
Risk of Failure		_	0.722
Safety Concern		_	0.725
Accident Rate (related to surface condition)		_	0.713
Scheme Cost		_	0.725
Available Funding		_	0.723
Whole Life-cycle Cost		_	0.726

Table 5.5: The Results of Reliability Analysis

Validity is concerned with whether the research measures or evaluates what the researcher intended to measure or evaluate (Badri, et al. 1995; Collis and Hussey, 2009; Saunders et al., 2012; Zohrabi, 2013). In order to assess the validity, three methods are outlined (Badri et al., 1995):

- Content validity;
- External validity or Predictive validity or Criterion-related validity;
- Construct validity.

Content validity depends on the judgements and evaluations of the researchers on whether the measurement instrument (the questionnaire) provides adequate coverage for all aspects of each item being measured. Judgement can be made through an extensive review of literature and prior discussion with others, or by using a panel of individuals to assess the measures (Badri et al., 1995; Saunder et al,. 2012).

In this research, the determination of the measurement criteria in the survey was based on literature review. Therefore, a pilot survey was conducted to seek feedback from two postgraduate researchers from the University of Manchester and three specialists in pavement maintenance within local road authorities to assess the measurement items, and whether the items cover all the investigative questions. The items were refined and edited according to the participants' feedback and evaluation, therefore, it can be said that the survey measures in this research have content validity.

External validity is concerned with whether the outcomes of a work of research are applicable in other settings (Zohrabi, 2013). The method seeks how representative the surveys are, and whether the selected participants are appropriate. In this study, profiles of participants are highly relevant to the context. Participants in the questionnaire survey involved specialists in pavement maintenance from different local road authorities. Therefore, it can be said that the representation capability of the questionnaire for the outcomes is externally valid.

Construct validity is concerned with whether a measure measures the theoretical construct that it was designed to measure (Badri, et al., 1995). In this study, interviews are conducted for triangulation purposes, and the outcomes of the interviews showed similar trend questionnaire results. Therefore, the questionnaire survey can be considered to have construct validity.

5.10 Prioritisation of the Factors for Pavement Maintenance using AHP Method

Due to the multiple criteria inclusion of the project, in order to achieve the decision goal, the study requires embedding a multi-criteria decision method for conducting a multi-criteria decision analysis (MCDA).

MCDA aids decision makers in analysing possible actions or alternatives based on multiple incommensurable factors/criteria. In other words, utilizing a decision system that deals with multiple criteria assists decision makers with to rating or ranking the alternatives (Eastman, 2009). For mainstream practitioners of MCDA, it differs from quantitative optimisation in a way that concerns of subjectivity is also taken into consideration in quantitative approaches that structure and formulate a decision making problem (Belton and Stewart, 2002; Roy, 2005).

MCDA methods are clustered as follows (Hobbs and Meier, 2000):

Outranking Methods:

- ELECTRE family (ELECTRE 1-2-3)
- PROMETHEE family (1&2)
- Regime Method Analysis

Value or Utility Function-Based Methods:

- Multi Attribute Utility Theory (MAUT)
- Simple Multi Attribute Rated Technique (SMART)
- Analytical Hierarchy Process (AHP)
- Simple Additive Weighting (SAW)

Other Methods:

- Novel Approach to Imprecise Assessment and Decision Environment (NAIADE)
- Stochastic Multi-objective Acceptability Analysis (SMAA)

As stated above, there are numerous MCDA methods developed to meet the needs of specific decision goals. Toloie-Eshlaghy and Homayonfar (2011) have conducted a comprehensive literature review, based on 20 scholarly journals published between 1999 and 2009 and classified MCDA methods in accordance with the application areas (See Table 5.6). MCDA methods and their implementation frequencies related to transportation studies are highlighted in the stated table. The numbers stated in the table represent the numbers of published papers for each field.

Method / Application	AHP	ANP	SAW	TOPSIS	ELECTRE	LA	GP	MOP	VIKOR	DEMATEL	PROMETHEE	SMART	FMCDM	Group MCDM	Group Decision Making	multiple criteria analysis	MAUT/MAVT	Compromise Programming	SMAA	OWA	DSS	DEA	choquet integral	rough sets Theory	Fuzzy set theory	Heuristic Algorithms	Other Methods	Total (Fuzzy/Crisp)	Total
Environment	3				1			1			3			1	1	2	1	2	1		9						2	27	32
Management	1												3								1							5	
Water Management	5		1	1	2		1				3					3	2	3		1	2				1		3	28	29
																				1								1	
Business and Financial	9	4	1	5	1		2	1	1	1	1				1	1	1				1	1		1			7	39	65
Management	5	2		2									8	1							1				5		2	26	
Transportation and	14	11		8			6	7	2	1	2	1			2	1			1		2	2	2			5	12	79	118
Logistics	9			3	1		2	4	1			1	4	2											8		2	39	
Manufacturing and	4	1		1			1	5	1						1		1	1			3	2				8	5	34	48
Assembly	4			1			1				1		4	1											2			14	
Energy Management	5				2			3			3				1	1					1						5	21	24
													2												1			3	
Agricultural and	1						2									1	3				2						3	12	12
Forestry Management																												0	
Managerial and	9	6		3	1	1	2	4		1	4				2	1	1				1	2				1	8	47	58
Strategic Planning	3			1			1						5								1							11	
Project Management	11	4		4			3	1		1					2	1					2	1			1		9	40	51
and Evaluation	6												1	1							3							11	
Social Service	1	2		1			1	3																			3	11	12
				1																								1	
Military Service	2			1				1			1	1									1						3	10	13
															1						1				1			3	
Other topics	7	3	1	4				4			1	1	2				1		1		1	1	2		2		8	39	50
	3	1		1									4														2	11	
	38	3	2	10	7		15	16	3	1	3	1		1	4		7	1	8	6	12	8	6	2		4	72	230	274
Non application Papers													1																
	2			5				3					1					2							12		9	44	
Total	142	37	5	54	15	1	37	53	8	5	22	5	4 4	7	15	11	1 7	9	11	8	44	17	10	3	33	18	155	786	786

Table 5.6: Classification of MCDA Methods According to the Application Areas (Toloie-Eshlaghy and Homayonfar, 2011)

Identification of weighting factors for the criteria is to be carried out via an appropriate method. There are three steps in utilizing any decision-making technique involving numerical analysis of alternatives (Triantaphyllou et al., 1998):

- Determining the relevant criteria and alternatives.
- Attaching numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.
- Processing the numerical values to determine a ranking of each alternative.

When selecting a suitable MCDA method, researcher considers the following:

- Ease of use
- Ability to support large number of decision makers
- Ability to handle data comprising different units (such as climate data and smart meters)

Overlapping these considerations with the classification supplied in the Table 5.6, Analytical Hierarchy Method (AHP) appears to be a frequently used method in transportation and pavement management field and arises as the suitable method for adoption.

Saaty (1980) concluded that in order for a problem to be represented and priorities to be developed for alternatives based on the user's judgment, AHP as a multi-criteria decision method is useful, as the method uses hierarchical structures. Steps are followed in order in the AHP procedure (Ibraheem and Atia, 2012):

1- Defining the problem.
2- Developing hierarchical structures.
3- Pairwise comparison.
4- Estimating relative weights.
5- Testing consistency.
6- Obtaining overall rating.

Once the rating of local road authorities' professionals on factors affecting pavement maintenance prioritisation is performed, the AHP method is applied so as to illustrate the prioritisation of the given factors. According to AHP, factor weights are yielded through conducting pairwise comparisons of rated factors with a view to establishing an Importance Matrix (IM). The latter, in turn, yields a more precise ranking of factors organized according to their significance. The normalisation of the paired matrix provides the importance attached to each factor. The design of the Importance Matrix can be seen below (Ibraheem and Atia, 2012):

$$A = \begin{bmatrix} 1 & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & 1 \end{bmatrix} \tag{5.1}$$

Where,

w_1 = rating value for factor 1 (F_1),

w_2 = rating value for factor 2 (F_2),

w_n = rating value for factor n (F_n).

Table 5.7 below shows the rating values for the 14 factors.

Factors	Rating Values for Factors w	
F_1	w_1	4.15
F_2	w_2	3.87
F_3	w_3	3.91
F_4	w_4	3.84
F_5	w_5	3.28
F_6	w_6	4.21
F_7	w_7	3.21
F_8	w_8	3.72
F_9	w_9	3.88
F_{10}	w_{10}	4.31
F_{11}	w_{11}	3.96
F_{12}	w_{12}	3.27
F_{13}	w_{13}	4.48
F_{14}	w_{14}	3.76

Table 5.7: Rating Values for Factors

With regard to the survey questionnaire that has been carried out, the weights of each single factor are the elements of the rating methodology employed for the evaluation of alternatives (roads). Upon pairwise comparison of the factor rating values of the survey questionnaire (as per table 5.7), Figure 5.7 is produced via Excel:

$$
A = \begin{bmatrix}
1 & 1.072351 & 1.061381 & 1.080729 & 1.265244 & 0.985748 & 1.292835 & 1.115591 & 1.069588 & 0.962877 & 1.04798 & 1.269113 & 0.926339 & 1.103723 \\
0.932530 & 1 & 0.989770 & 1.007813 & 1.179878 & 0.919240 & 1.205607 & 1.040323 & 0.997423 & 0.89712 & 0.977273 & 1.183486 & 0.863839 & 1.029255 \\
0.942169 & 1.010336 & 1 & 1.018229 & 1.192073 & 0.928741 & 1.218069 & 1.051075 & 1.007732 & 0.907193 & 0.987374 & 1.195719 & 0.872768 & 1.039894 \\
0.925301 & 0.992248 & 0.982097 & 1 & 1.170732 & 0.912114 & 1.196262 & 1.032258 & 0.989691 & 0.890951 & 0.969697 & 1.174312 & 0.857143 & 1.021277 \\
0.790361 & 0.847545 & 0.838875 & 0.854167 & 1 & 0.779097 & 1.021807 & 0.881720 & 0.845361 & 0.761021 & 0.828283 & 1.003058 & 0.732143 & 0.872340 \\
1.014458 & 1.087855 & 1.076726 & 1.096354 & 1.283537 & 1 & 1.311526 & 1.131720 & 1.085052 & 0.976798 & 1.063131 & 1.287462 & 0.939732 & 1.119681 \\
0.773494 & 0.829457 & 0.820972 & 0.835938 & 0.978659 & 0.762470 & 1 & 0.862903 & 0.827320 & 0.744780 & 0.810606 & 0.981651 & 0.716518 & 0.853723 \\
0.896386 & 0.961240 & 0.951407 & 0.968750 & 1.134146 & 0.883610 & 1.158879 & 1 & 0.958763 & 0.863109 & 0.939394 & 1.137615 & 0.830357 & 0.989362 \\
0.934940 & 1.002584 & 0.992327 & 1.010417 & 1.182927 & 0.921615 & 1.208723 & 1.043011 & 1 & 0.900232 & 0.979798 & 1.186544 & 0.866071 & 1.031915 \\
1.038554 & 1.113695 & 1.102302 & 1.122396 & 1.314024 & 1.023753 & 1.342679 & 1.158602 & 1.110825 & 1 & 1.088384 & 1.318043 & 0.962054 & 1.146277 \\
0.954217 & 1.023256 & 1.012788 & 1.031250 & 1.207317 & 0.940618 & 1.233645 & 1.064516 & 1.020619 & 0.918794 & 1 & 1.211009 & 0.883929 & 1.053191 \\
0.787952 & 0.844961 & 0.836317 & 0.851563 & 0.996951 & 0.776722 & 1.018692 & 0.879032 & 0.842784 & 0.758701 & 0.825758 & 1 & 0.729911 & 0.869681 \\
1.079518 & 1.157623 & 1.145780 & 1.166667 & 1.365854 & 1.064133 & 1.395639 & 1.204301 & 1.154639 & 1.039443 & 1.131313 & 1.370031 & 1 & 1.191489 \\
0.906024 & 0.971576 & 0.961637 & 0.979167 & 1.146341 & 0.893112 & 1.171340 & 1.010753 & 0.969072 & 0.872390 & 0.949495 & 1.149847 & 0.839286 & 1
\end{bmatrix}
$$

Figure 5.7: Calculated Importance Matrix (Paired Matrix)

To calculate the relative weights of factors in the pairwise comparison matrix, eigenvalue method is used. The relative weights (*W*) of matrix *A* are obtained from the following equation (Ibraheem and Atia, 2012):

$$(A - \lambda_{\max} I) \times W = 0 \qquad (5.2)$$

Where,

$\lambda_{\max}$ = the biggest eigenvalue of matrix *A*

I = unit matrix

Let *A* = [a_{jk}] for the n x n matrix and the following vector equation is considered:

$$Ax = \lambda x \qquad (5.3)$$

Where,

X: unknown vector

λ :unknown scalar

"A value of λ for which ($Ax = \lambda x$) has a solution $x \neq 0$ is called eigenvalue or characteristic value of matrix *A*. The corresponding solutions $x \neq 0$ of ($Ax = \lambda x$) are called eigenvectors or characteristic vectors of matrix *A* corresponding to that eigenvalue λ" (Ibraheem and Atia, 2012).

The steps of determination of eigenvalues and eigenvectors are illustrated in terms of matrix (5.4):

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{5.4}$$

Eigenvalues are determined first as in equation (5.5).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \lambda \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \tag{5.5}$$

Written out in components,

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = \lambda x_1$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n = \lambda x_2$$

………………………………..

$$a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nn}x_n = \lambda x_n$$

Transferring the terms on the right to the left,

$$(a_{11} - \lambda)x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = 0$$

$$a_{21}x_1 + (a_{22} - \lambda)x_2 + \cdots + a_{2n}x_n = 0$$

……………………………………

$$a_{n1}x_1 + a_{n2}x_2 + \cdots + (a_{nn} - \lambda)x_n = 0$$

This can be written in matrix notation,

$$(A - \lambda I)x = 0 \tag{5.6}$$

"By Cramer's Theorem, this homogeneous linear system of equations has a nontrivial solution if the corresponding determinant of the coefficients is zero" (Ibraheem and Atia, 2012):

$$D(\lambda) = \det(A - \lambda I) = \begin{bmatrix} a_{11} - \lambda & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} - \lambda & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} - \lambda \end{bmatrix} = 0 \tag{5.7}$$

$D(\lambda)$ is called the characteristic determinant and equation (5.7) is called the characteristic equation of the matrix A.

Eigenvalue $\lambda_{\max}$ and the eigenvector (Weights of Factors) are calculated via MATLAB R2015a computation software (see Appendix F) and the results are shown below:

$$\lambda_{\max} = 14$$

$$\begin{bmatrix} 0.077064 \\ 0.071854 \\ 0.072606 \\ 0.071317 \\ 0.060899 \\ 0.078191 \\ 0.059610 \\ 0.069089 \\ 0.072042 \\ 0.080044 \\ 0.073546 \\ 0.060738 \\ 0.083186 \\ 0.069814 \end{bmatrix}$$

Weights of Factors (Eigenvector)

The following Figure 5.8 shows the normalised factors' weight of importance. The sum of all factors is equal to 1.

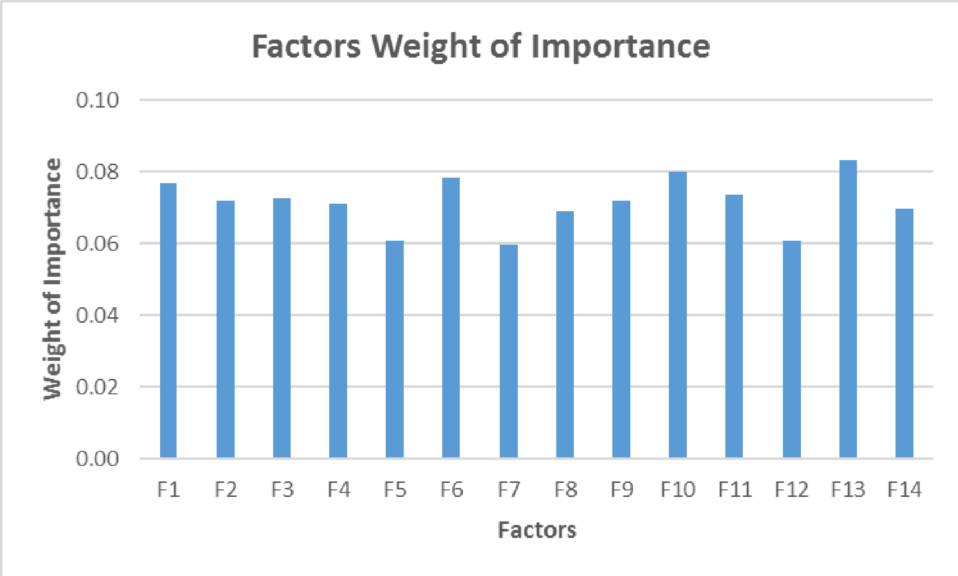


Figure 5.8 Factors' Weight of Importance

The outcome shows that the ranking sequence does not differ from the one in Table 5.3. Normalised factor weights singled out F13 as the most crucial factor (0.083186 out of 1), and F7 as the most negligible factor (0.059610 out of 1). According to Saaty (2008), the consistency ratio (CR) demonstrates the degree of compatibility of data analysed through the AHP method. By definition, the consistency ratio reveals any potential incompatibility in subjective matrix scores. For the latter to be deemed acceptable, the consistency ratio should be less than or equal to 0.1.

The consistency ratio formula is:

$$CR = CI / RI \qquad (5.8),$$

where CI stands for the consistency index, and RI – for the random index:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (5.9)$$

The formulas above demonstrate calculating consistency with regard to the largest eigenvalue.

The largest eigenvalue λmax (allowing for deviations owing to the large numbers) is obtained via MATLAB R2015a computation software as "14", and when it is applied within the equation given above, where n is the size of the matrix, CI is calculated as "0".

In random matrices, the RI is the mean value of CI. RI values for the matrices comprising N elements (for different matrix orders) are shown in Table 5.8 (Ibraheem & Atia, 2012):

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Table 5.8: Average Random Consistency (*RI*) (Ibraheem & Atia, 2012)

This study employs an order of magnitude of the pairwise comparison matrix equal to 14, which yields an RI value of 1.57. The consistency ratio of the comparison process is then calculated by means of the CI and RI values obtained above:

CR = CI / RI = 0 / 1.57 = 0

The CR value being lower than 0.1 means that consistency is corroborated in the comparison process.

5.11 Summary of Chapter Five

Chapter Five has established the most significant pavement maintenance prioritisation factors. These factors have been derived based on a consensus of 67 practising Local Road Authority Road Managers, as specialists in their field, representing a 34% response rate to the questionnaire survey carried out for this purpose.

Having established the factors that influence pavement maintenance prioritisation decision making, these factors and their obtained weighted ranking have been taken forward to the next stage for structuring the proposed GIS-based pavement maintenance management model, which is the subject of the following chapter.

Concisely, factors for pavement maintenance are established, followed by determining their relevance for maintenance priority by means of the AHP pairwise comparison methodology used for analysing the responses to the survey questionnaire. The conclusions shall be applied to the process of ranking of alternative roads.

The next chapter will specify a conceptual model of the proposed pavement maintenance management approach. A GIS-based decision support model is proposed for effectively managing pavement maintenance.

Chapter Six

Conceptual Model of Proposed Pavement Maintenance Management Approach

6.1 Introduction

Based on the findings from the literature review, questionnaire survey, and interviews, it is essential to develop a GIS-based Pavement Maintenance Management model to manage pavement maintenance effectively. This chapter deals with the structure of the proposed model. The proposed model includes the affecting factors, which are determined from the literature review stage, and the rating of importance of these factors. This model should also take into account the need of local road authorities for such a model.

As an initial step, or general structure of decision support, the relevance of an SDSS (Spatial Decision Support System) for pavement maintenance prioritisation and the use of GIS in pavement maintenance are reviewed. Subsequently, the structure and functionality of the model under consideration are covered. Finally, the evaluation methods and the foreseen output of the model under consideration are discussed.

6.2 Decision Support Requirements in Pavement Maintenance Management

In carrying out pavement maintenance work, many factors, other than the observed pavement condition, have to be considered for maintenance prioritisation. However, because of the inadequate funding levels available for pavement maintenance and management each year, decisions have to be made to implement work that provide the highest value of return to the road network in general. Therefore, a Multi-Criteria Decision Making (MCDM) approach is necessary to ensure a satisfactory trade-off between conflicting factors and the optimisation of the results.

In this section, the MCDM approach in pavement maintenance is briefly covered. Subsequently, analysis applications for pavement management are evaluated from a spatial perspective, and GIS as a decision support tool in pavement maintenance is reviewed.

6.2.1 Multi-Criteria Decision Making (MCDM) in Pavement Maintenance

Ibraheem and Atia (2012) concluded that Multiple Criteria Decision Making (MCDM) methods are convenient for solving practical complex problems, such as the prioritisation of maintenance works for the overall road network.

However, there are many methods on MCDM and the common method used is the Analytical Hierarchy Process (AHP) that is based on pairwise comparisons on ratio scale, which is used to solve complex decision problems (Ibraheem and Atia, 2012).

Farhan and Fwa (2009) concluded that the use of the AHP method for pavement maintenance prioritisation is appropriate. Moazzami et al. (2011) used the AHP method in priority rating of pavement maintenance and concluded that AHP is suitable for prioritisation of a large number of alternatives.

6.2.2 Spatial Analysis Applications for Pavement Management

Spatial analysis technologies are useful alternative tools for PMMS because pavement and asset management systems are supported with the compilation of a tremendous amount of information, available in a wide array of referencing systems, formats, and media (Flintsch and Chen, 2007). The application assists in the analysis of several planning and operational problems on pavement management that include scale, time, and format, whereas measurement, mapping, monitoring, and modelling of spatial phenomena is enhanced (Miles and Ho, 1999). This technology has the capability to efficiently integrate, store, and query spatially referenced data to support many pertinent decision processes.

Goodchild & Longley (1999) define these as a collection of methods that are effective spatial data. These combine manipulations, transformations and other techniques that show the less obvious patterns and anomalies that could enhance and support decisions on road pavement prioritisation. These data form geographical features referenced by positions and attributes in analogue or readable digital formats (OMB, 2010). Spatial analysis lets a user query, map, create, and analyse cell-based raster data, and conduct comprehensive raster or vector analysis.

Spatial applications generate a simplistic view of a complex system. The technology relies on the branch of geometrical mathematics, topology, which concerns spatial relationships that correlate spatial entities. Topology is about the connectedness, adjacency, enclosure, and other geometric properties of objects (NHI, 1997).

Applications in this dimension facilitate data integration which could be traffic and Maintenance and Rehabilitation (M&R) history or inventory, data collection which includes the processing of gap detection among others, and output presentation such as the average pavement condition. Their functions are extensive so that even weather information could be used to develop pavement performance models, or apply land use policy and traffic predictions into regional development models (Flintsch et al., 2004).

A spatial tool is designed to support the capture, manipulation, analysis, modelling, and display of spatially-referenced data through a system of computer hardware, software, personnel, organisations, and business processes. It is principally applied for solving comprehensive management and planning problems (Lewis & Sutton, 1993).

The appropriate selection of spatial tools, developing the right base map, and correlating these attributes in spatial and cartographic information is a crucial concern in the development and implementation of spatially supported Pavement Maintenance Management Systems (PMMS) tools (AASHTO, 2001).

6.2.3 GIS as a Decision Support Tool in Pavement Maintenance

Pavement Maintenance Management Systems (PMMSs) with spatial application capabilities are employed as decision support mechanisms in the protection and management of investment (Flintsch & Chen, 2007). That is, PMMSs are developed at a local level to enhance the process of decision-making, more specifically, to gain an insight into the implications of decisions, and limit adverse impacts and maintenance costs. The fact that the PMMS incorporates technology is considered essential for promoting and enhancing decision-making (Abo-Hashema et al., 2006).

GIS is a remarkable tool that supports and enhances new techniques for the proper collection, archiving, and analysing of pavement maintenance data (Abo-Hashema et al., 2006). Improvements in the GIS capabilities enhance applications on road inventory, budgeting, prioritising techniques and maintenance decisions (Alter, 1992).

Nevertheless, pavement maintenance is not an exact science. It is expected that two different road segments of the same type do not have the same repair methods. Each road segment location requires good judgement by experienced personnel (Haas et al., 1994). Keeping pavement condition to an acceptable level entails routine maintenance work in the form of removing surface corrugation, patching, filling ruts, pouring cracks, bleeding surfaces, among others. Rehabilitation, overlays, and resurfacing are considered major maintenance activities (AASHTO, 1993).

Aging roads are more vulnerable to natural disasters, which often disrupts the service provided by these road networks (Housner and Thiel, 1995). Road maintenance entwines utility works, also making it difficult to independently address road network maintenance activities. Installations on new utility lines interrupt road maintenance schedules, especially in regions where the mere size of the network and number of roads constrain maintenance and repair programmes. It is one reason why the broadening GIS applications are more extensively integrated into PMMS (Rhind, 1989).

Adeleke et al (2015) reported how GIS is used as a decision support tool for pavement maintenance, and recommended that in order to enhance the decision making process, road agencies should consider the use of GIS for pavement maintenance management. In addition, the use of GIS as a spatial technology is appropriate for pavement maintenance management as the data used in the decision making process in pavement management systems have spatial components (Adeleke et al., 2015).

6.3 Proposed Conceptual Model

The features of the above-mentioned model aiding decision-makers in selecting prioritised roads for pavement maintenance are outlined below. First, a description of the functions the model can perform is provided in order to justify its proposed application, followed by an outline of the data requirements of the model and its components.

6.3.1 Functionality of Model

In this study, data processing and analysis are based on the Analytic Hierarchy Process (AHP). Ibraheem and Atia (2012) concluded that Multiple Criteria Decision Making (MCDM) methods are convenient for solving practical complex problems, such as the prioritisation of maintenance works for the overall road network. However, Saaty (2008) considered AHP as a quantitative technique for MCDM, where it initially identifies the objectives, criteria and alternatives for a problem. AHP is adopted in this study for estimating the relative weights of different factors that are considered in the spatial analysis process to the case of prioritising pavement maintenance.

The AHP method is applied in two steps:

1. Calculating the factors' relative weights (Figure 6.1)
2. Calculating the order of priority of the alternatives (roads) (Figures 6.2 and 6.3)

Chapter 5 deals in detail with the mechanism of determining factor weights so it is only schematically presented here as step one in utilising the AHP method. Figure 6.1 shows the breakdown of factor weights. The next stage of the process involves the evaluation of individual roads on the basis of each factor. In turn, Figure 6.2 illustrates the juxtaposition of factors against alternative roads.

The last step of the AHP algorithm as per Figure 6.3 yields the vector of the alternative ranking, expressed as the product of the priority matrix and the factor weight vector. The specific data of the factors for each road are discussed in the following chapter.

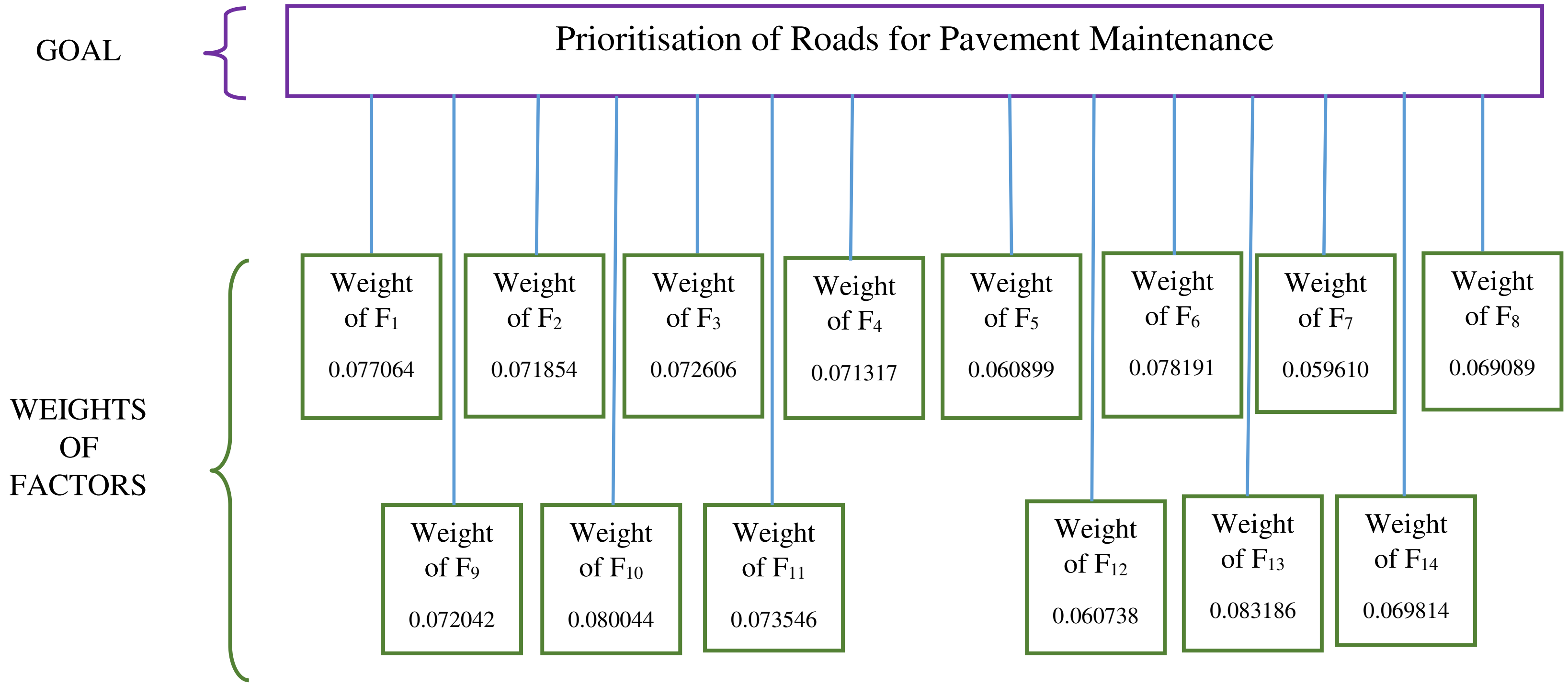


Figure 6.1: Relative Weights of Factors

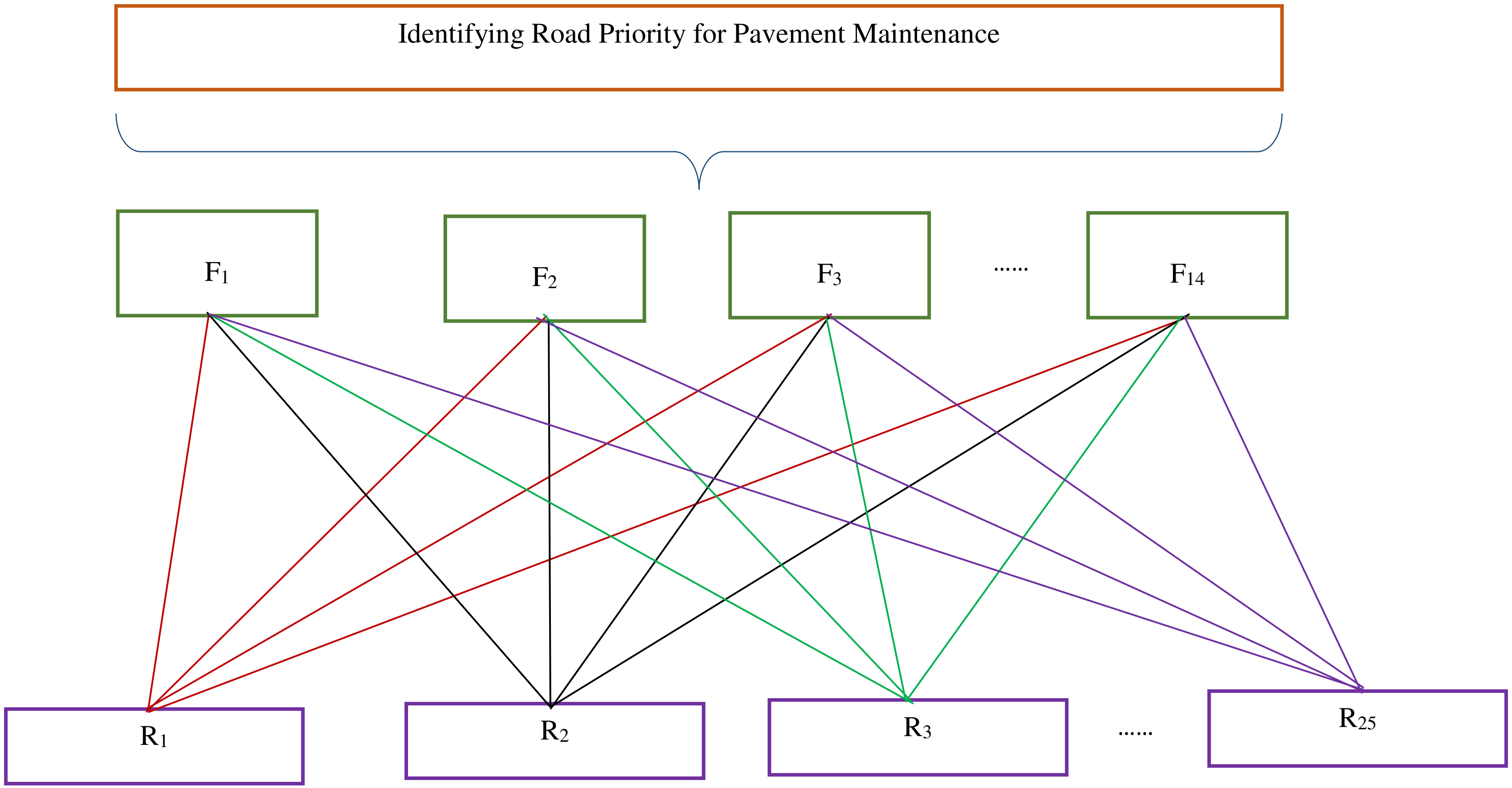


Figure 6.2: Roads Prioritisation Mechanism

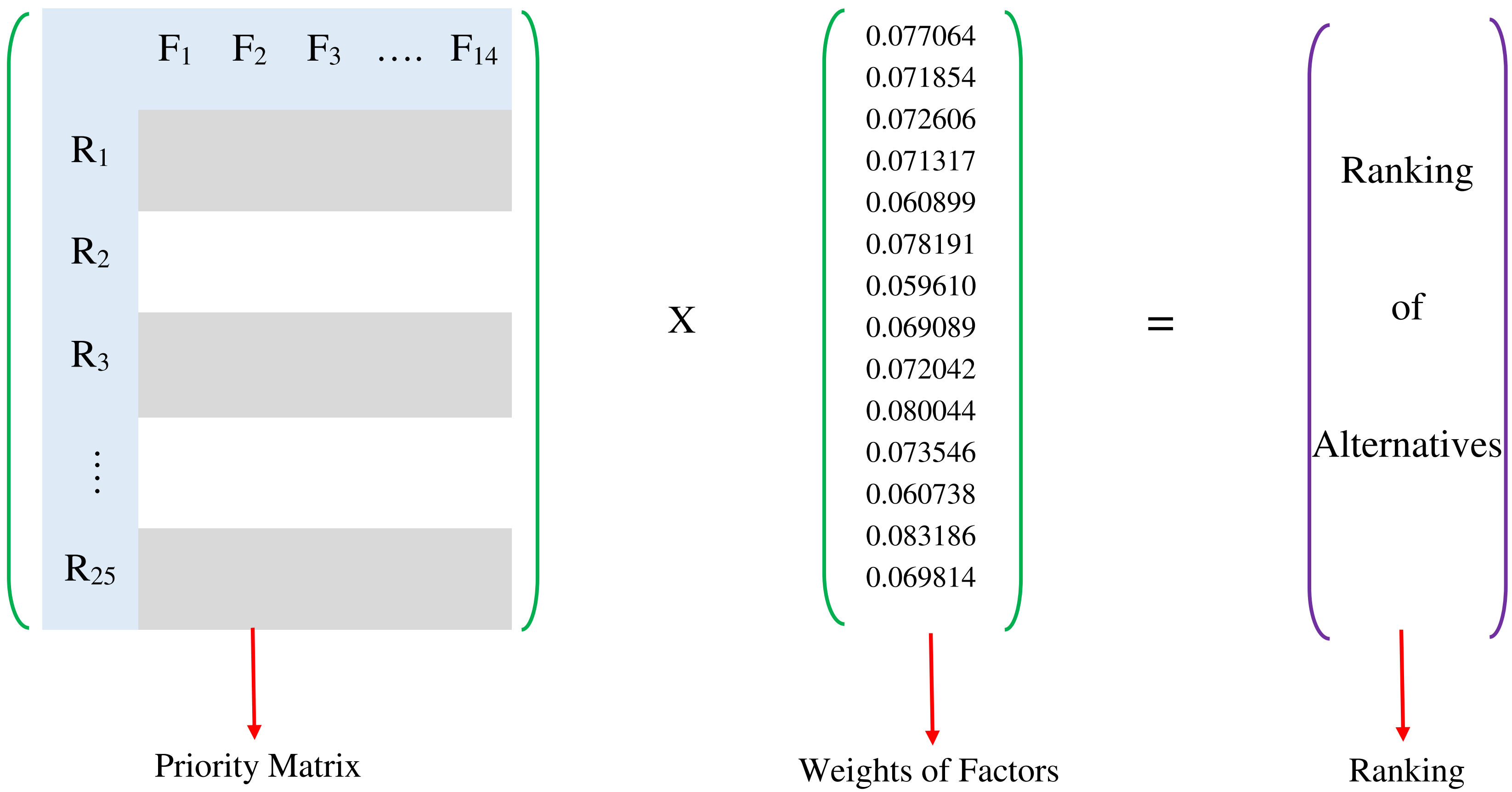


Figure 6.3: Calculation of Ranking of Alternatives

6.3.2 Directives Defining the Data Employed in the Model

The processes of gathering, assessment and analysis of primary data have already been discussed in Chapter 5. This input constitutes a crucial step in formulating the evaluation process of ranking alternative roads on the basis of pavement maintenance. It is essential that alternative roads are categorized with regard to their spatial components based on the reviewed parameters so as to make evaluation possible as foreseen.

6.3.2.1 Base Map

Spatial data modelling necessitates the availability of a topographic base map in geographical information system software, which would serve as a foundation to be further populated with other additional data. This thesis uses a map of Runnymede District in Surrey as a base map providing a comprehensive network of individual roads.

6.3.2.2 Remaining Service Life

Remaining Service Life is "the number of years that a pavement will be functionally and structurally in an acceptable condition with only routine maintenance" (Gedafa, et al., 2010). Remaining Service Life data is very important for pavement maintenance as it partially determines the type of treatment that can be applied. Many local road authorities consider the remaining service life to be the most fundamental data required to manage the road network effectively. However, this is the most difficult data to accurately obtain.

6.3.2.3 Road Condition Indicator (RCI)

RCI is the national statistical indicator that tends to guide towards a potential problem. However, the survey data beneath the RCI can be useful, such as cracking, rutting, texture etc. RCI is an important guidance, but its data should be validated and investigated further, as some data can be misleading.

6.3.2.4 Type of Deterioration

Type of Deterioration informs of the nature of repair treatment and intervention point. Knowing the reasons for deterioration is fundamental information in the process of major maintenance intervention and repair.

6.3.2.5 Observed Deterioration Rate

This information is typically available from the annual condition surveys. The Observed Deterioration Rate informs the change point between intermediate surface treatment and longer term.

6.3.2.6 Traffic Diversion

Traffic Diversion represents the need for the diversion, the environmental impact of diverted traffic, the socio-economics of diverting traffic away from regular routes, increased journey length and the cost of implementing the traffic diversion.

6.3.2.7 Importance/Classification of Road

Road classification indicates the importance of the road, and the typical use of the road is a very important factor when prioritising major maintenance works, in order to ensure the critical routes serviceable.

6.3.2.8 Annual Average Daily Traffic (AADT)

AADT represents the daily traffic volume, which indicates the actual use of the road, and that helps to determine treatment design and necessary pavement depth/strength.

6.3.2.9 Possible Conflict or Overlap with Other Road Works

The aim of local road authorities' asset management is to maximise the life of any treatment on the network. One of the main ways to achieve this is to ensure that local road authorities co-ordinate with other road works including utilities, so that any maintenance proposal is the final process on a stretch of road for many years to come.

6.3.2.10 Risk of Failure

One of the focuses of local road authorities' asset management is to ascertain the level of risk of potential failure of pavement. Whilst funding is still available to local road authorities, roads will still be prioritised if there is an immediate risk of failure.

6.3.2.11 Safety Concern

Safety Concern should ideally be resolved by immediate response to mitigate danger by repairs or warning. Safety inspections and repair are the responsibility of routine maintenance teams within local road authorities. However, there may be exceptions that need to be identified or accelerated.

6.3.2.12 Accident Rate (related to surface condition)

Accident Rate factor can receive a high priority to avoid future litigation if accidents are attributable to a road surface issue. However, road condition is a contributory factor in accidents' rate.

6.3.2.13 Scheme Cost

Scheme Cost is considered in prioritisation for programming a scheme befor it deteriorates to a deeper form of construction. Most local road authorities are massively underfunded when comparing typical capital and revenue funding allocations with life-cycle cost model requirements.

6.3.2.14 Available Funding

The gap between available funding and steady state network condition funding continues to widen year on year, hence available funding is affecting the ability to maintain the road network efficiently. Available Funding is the ultimate criterion in pavement maintenance, as it determines the asset management strategy, treatment response and timing of repairs.

6.3.2.15 Whole Life-cycle Cost

Ideally, Whole Life-cycle Cost would be the highest priority for pavement maintenance if sufficient funding were available to local road authorities. However, it could be too heavy on initial capital cost, which may not be affordable. For asset management, this remains the fundamental financial consideration and maintenance driver when capital investment in the road network is proposed. However, in the political world, this is constantly being compromised with the pressure on local road authorities needing to be seen to be doing more work on the ground, rather than solutions appropriate for minimising life-cycle cost.

6.3.3 Structure of Proposed Model

A presentation of the model from two perspectives is offered. First, its main components and overall structure are discussed. Initially, the main components of the proposed model are represented. Five phases are included in the proposed model, representing the main components. Figure 6.4 illustrates the components of the proposed model for pavement maintenance management.

Phase 1 refers to identifying factors affecting pavement maintenance priority

Phase 2 refers to the processing mechanism and appropriate procedures to deal with the affecting factors (in this case, AHP algorithm).

Phase 3 refers to the classification and scoring of the model's parameters

Phase 4 refers to the application of the model for pavement maintenance priority

Phase 5 refers to the calculation of Pavement Maintenance Priority Score (PMPS)

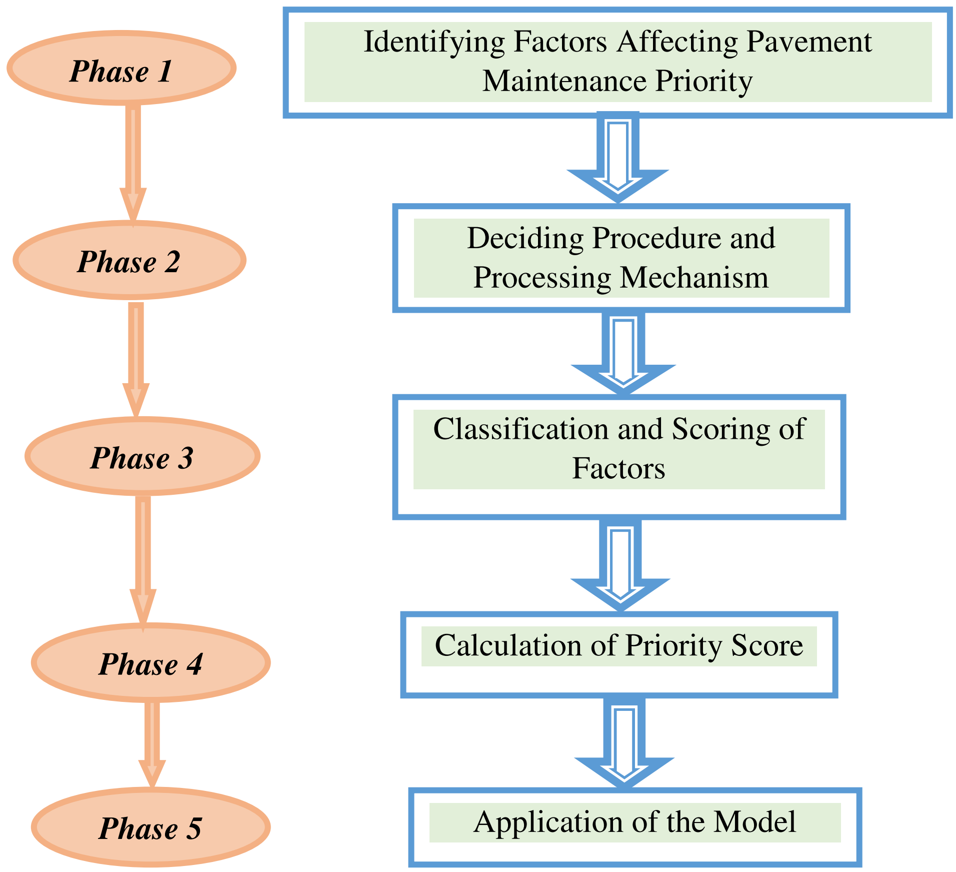


Figure 6.4: Components of the Proposed Model for Pavement Maintenance

6.3.3.1 Phase 1: Identifying Factors Affecting Pavement Maintenance Management

Before examining other components of the proposed model, it is essential to identify the factors that influence the prioritisation process of pavement maintenance. These factors can influence the performance and efficiency of the model.

In this research, 14 important factors have been identified through literature review, which should be taken into account for the proposed model of pavement maintenance management.

6.3.3.2 Phase 2: Processing Mechanism and Appropriate Procedure

The Analytic Hierarchy Process (AHP) method will be adopted in this study for estimating the relative weights of different factors that are considered in the spatial analysis process to the case of prioritising pavement maintenance and determining the relative ranking of alternatives.

Calculation of weights of factors will be the first stage of the stated AHP algorithm, and the process of calculating factors' weights is described in detail in the previous chapter five. In order to determine the relative ranking of alternatives, a priority matrix should be determined via assigning scores for factors according to their classification, which will be achieved in the next phase.

6.3.3.3 Phase 3: Classification and Assigning Scale of the Model's Parameters

In this phase, the 14 factors affecting pavement maintenance priority will be used to compute the output priority scores for the proposed model. Therefore, classifying, describing factors and assigning classification scales is necessary. The tasks of classifying factors will mainly follow the recommendation of the "Code of Practice for Highway Maintenance Management – Well-maintained Highways", Association of Directors of Environment, Economy, Planning and Transport (ADEPT) and Road Surface Treatments Association (RSTA) report, Adlinge & Gupta (2008) and various related reports, and assigning classification scales will be scored by the researcher. However, some factors will also be classified and scored based on rational judgment.

As mentioned above, the scale of 1 to 3 will be used for the assigned data in the priority matrix, where 1 represents least attention for pavement to be maintained, 2 represents intermediate attention for pavement to be maintained, and 3 represents immediate attention for pavement to be maintained. Classification scales for the 14 factors will be discussed in detail in the following chapter 7.

6.3.3.4 Phase 4: Calculation of Pavement Maintenance Priority Score (PMPS)

The next step will be to calculate PMPS, which indicates the ranking of alternatives. This is done by multiplication of the priority matrix and the vector of factors' weights. The output of this calculation is the vector that indicates ranking of alternatives. The AHP algorithm used to calculate the Priority Score is presented as follows:

$$\begin{aligned} PMPS = [&(F_1 * W_1) + (F_2 * W_2) + (F_3 * W_3) + (F_4 * W_4) + (F_5 * W_5) + \\ &(F_6 * W_6) + (F_7 * W_7) + (F_8 * W_8) + (F_9 * W_9) + (F_{10} * W_{10}) + \\ &(F_{11} * W_{11}) + (F_{12} * W_{12}) + (F_{13} * W_{13}) + (F_{14} * W_{14})] \end{aligned} \quad (6.1)$$

Where,

F = Score of Factor (1 to 3)

W = Weight of Factor

6.3.3.5 Phase 5: Application of the Model for Pavement Maintenance Priority

The outcome of the calculated PMPS in phase 4 will be integrated into GIS to form the final model. Application of the final model is done by using a case study of Runnymede District within the Surrey County Council to test the proposed model. This will help to check that it can be used and applied within similar local road authorities**.**

Second, the conceptual distinctions of the model are outlined with an emphasis on the data fed into and out of it. The calculated AHP algorithm via Excel software is then integrated into the above-mentioned GIS platform. The conceptual diagram of the model is shown in Figure 6.5.

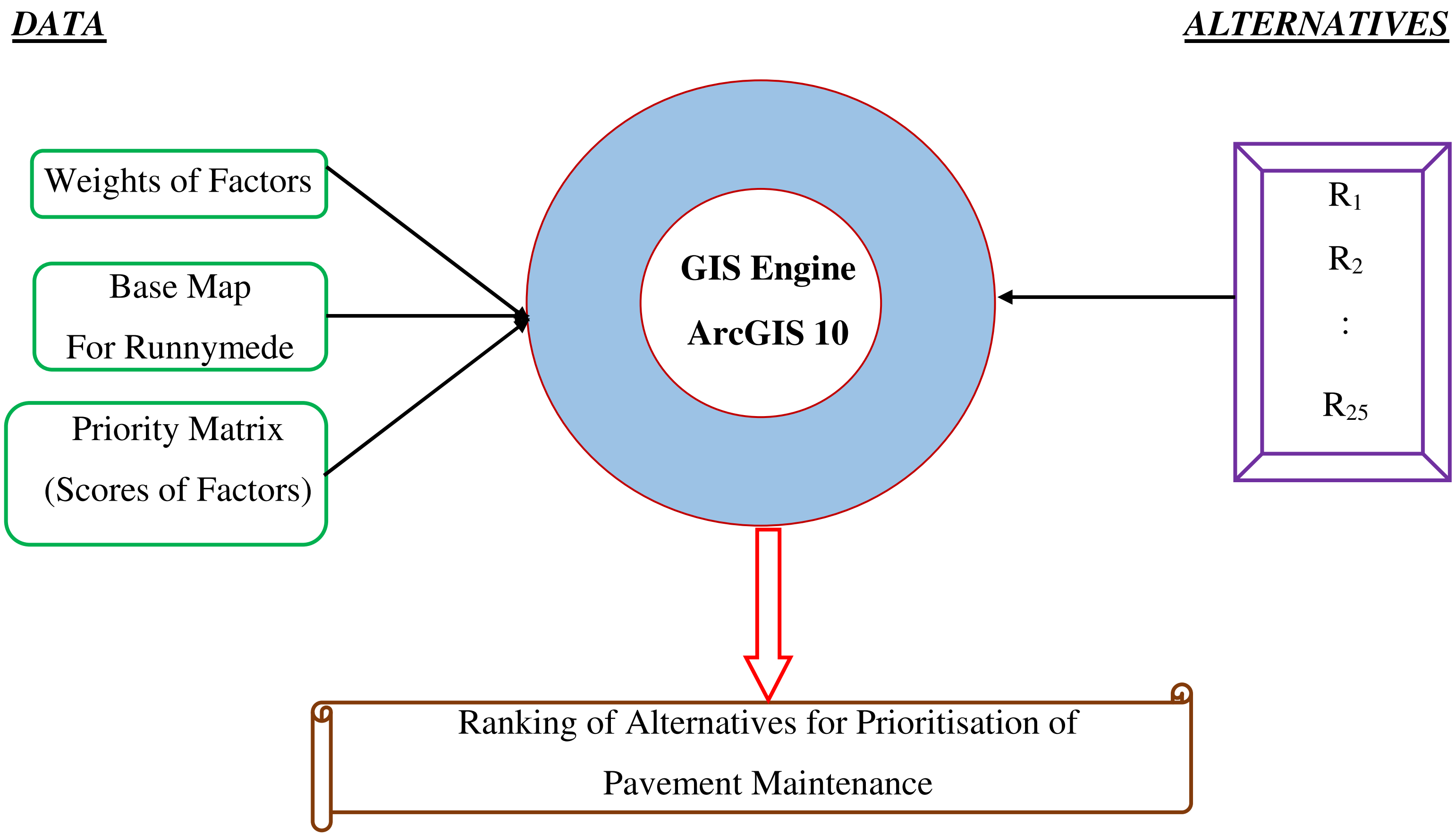


Figure 6.5: Proposed Conceptual Model for Prioritisation Pavement Maintenance

6.4 Summary of Chapter Six

In this chapter, a conceptual model of the proposed pavement maintenance approach is specified. Decision support requirements in pavement maintenance management are discussed, and the suitability of MCDM including the AHP method, spatial analysis and GIS as a decision support tool in pavement maintenance are reviewed. Therefore, the system is presented from the points of view of how it works as well as what data is needed for it to function properly.

Additionally, the components of the system are further elaborated on by applying the method of decomposition, and the conceptual framework of the model is represented through its processes of data input and output.

Chapter Seven

Prototype development of the model in GIS

7.1 Introduction

This chapter presents the prototype development of the model in GIS, and the testing stage of the model, to be utilised as a decision support tool in pavement maintenance prioritisation for the purpose of optimising the use of the limited available resources in pavement management in local road authorities. Figure 7.1 shows the location of Runnymede on the Surrey County map, and Figure 7.2 shows the location of Surrey County on the UK county map.

Figure 7.1 Location of Runnymede on Surry County Map. Source: GBMAPS (2015)

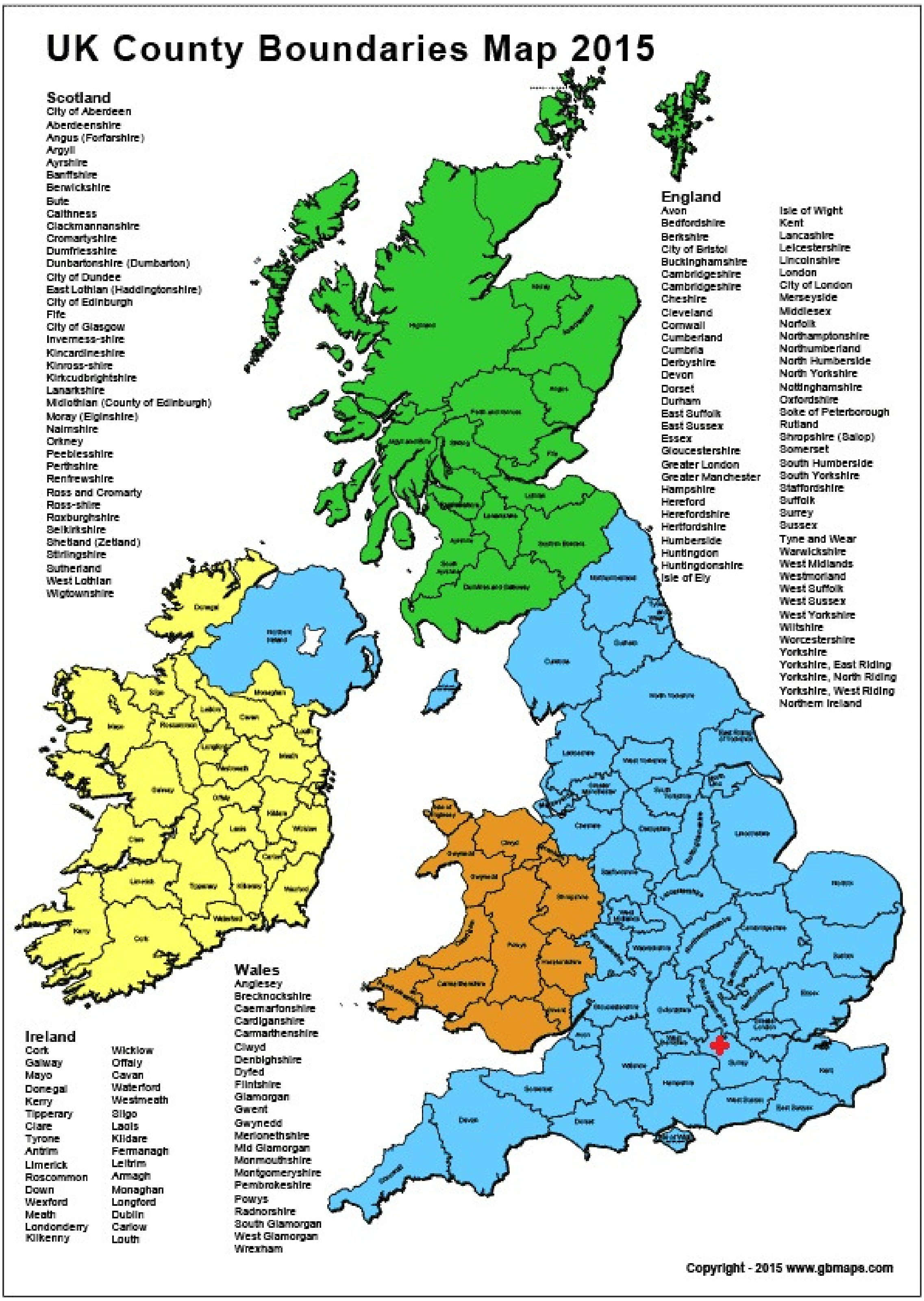


Figure 7.2: Location of Surrey on the UK County Map. GBMAPS (2015)

Initially, 25 roads in the Runnymede District in Surrey are used as the case study to test the proposed model. Figure 7.3 shows the background map of Runnymede in GIS.

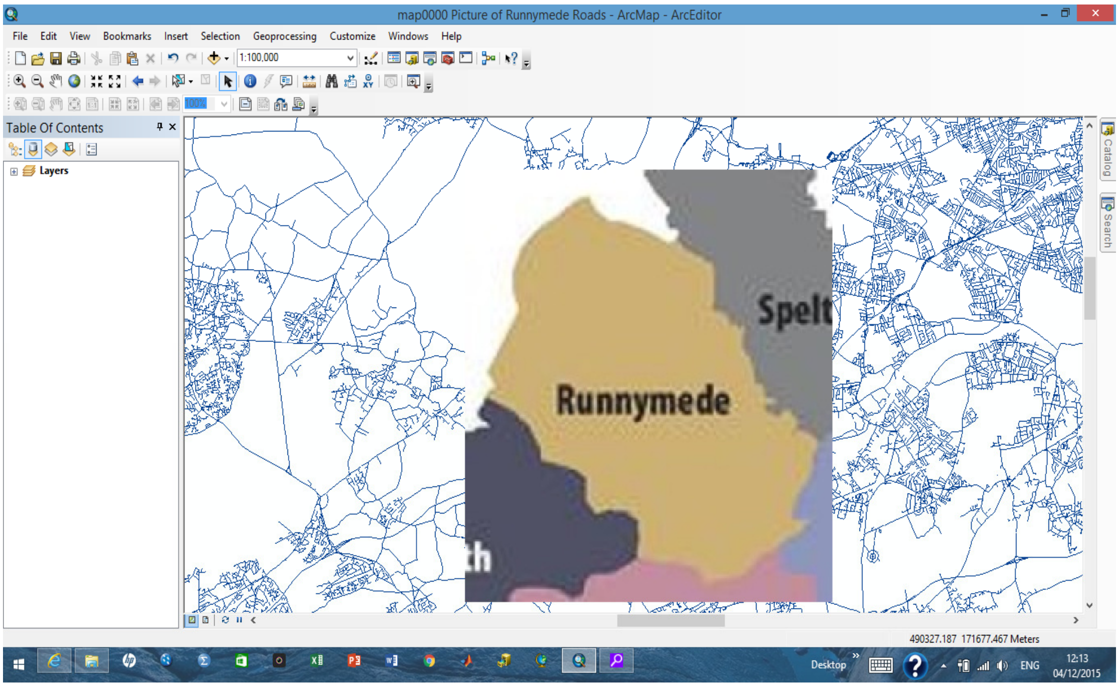


Figure 7.3: Runnymede Background Map in GIS. Source: (Ordance Survey)

The next step is to assign the data layer of Runnymede roads to the digital map, and then import the database for the calculated ranking of alternatives (roads) into ArcGIS software, which was calculated using the algorithm given in Figure 6.3 in chapter 6. When the calculation logarithm is used for individual road level, the following formulation is achieved for each road:

$$\begin{aligned} PMPS = [& \{(R_nF_1)*(0.077064)\} + \{(R_nF_2)*(0.071854)\} + \{(R_nF_3)*(0.072606)\} + \\ & \{(R_nF_4)*(0.071317)\} + \{(R_nF_5)*(0.060899)\} + \{(R_nF_6)*(0.078191)\} + \\ & \{(R_nF_7)*(0.59610)\} + \{(R_nF_8)*(0.069089)\} + \{(R_nF_9)*(0.072042)\} + \\ & \{(R_nF_{10})*(0.080044)\} + \{(R_nF_{11})*(0.073546)\} + \{(R_nF_{12})*(0.060738)\} + \\ & \{(R_nF_{13})*(0.083186)\} + \{(R_nF_{14})*(0.069814)\} \end{aligned} \quad (7.1)$$

Where,

PMPS = Pavement Maintenance Priority Score

n = the road number (where in this case n = (1, 2, 3, …. 25))

R = Road

F = Factor

R_nF_1 = Score of Factor 1 for n^{th} Road (where in this case, Score of Factor (1 to 3))

The numbers in parentheses = weights of factors that are shown in Figure 6.1 in chapter 6.

A scale of 1 to 3 is used for the factors according to their classification, and then the scores of the 14 factors for each factor 1 or 2 or 3 are assigned to each road to form the priority matrix. As no real data is available due to difficulties accessing that data, assumptions are made in order to assign a score for each factor, where 1 represents least attention for pavement to be maintained, 2 represents intermediate attention for pavement to be maintained, and 3 represents immediate attention for pavement to be maintained. The conclusion that can be drawn from the equation is that the greater the value of the solution, the greater the need for maintenance is. The values (PMPS) are listed in order of importance to determine and weigh the pavement maintenance priority of individual roads. It is worth mentioning that the priority ranking reflects the reversed PMPS arrangement comprising the entire number of roads. Thus the highest priority scored road is the first to be maintained.

7.2 Geographical Position of Runnymede's Roads

The case study roads used in this study are shown in a GIS map, where Surrey County Council provided the data for the base map layer, which consists of 25 different road classes (A, B, and C roads). The base map layer is developed by using ArcGIS 10 software, which is used by the researcher to add the relevant data for pavement maintenance prioritisation. Figure 7.4 shows the base map for Runnymede roads, which concludes the position of the 25 roads, and Table 7.1 below shows the names of the 25 roads used in the base map.

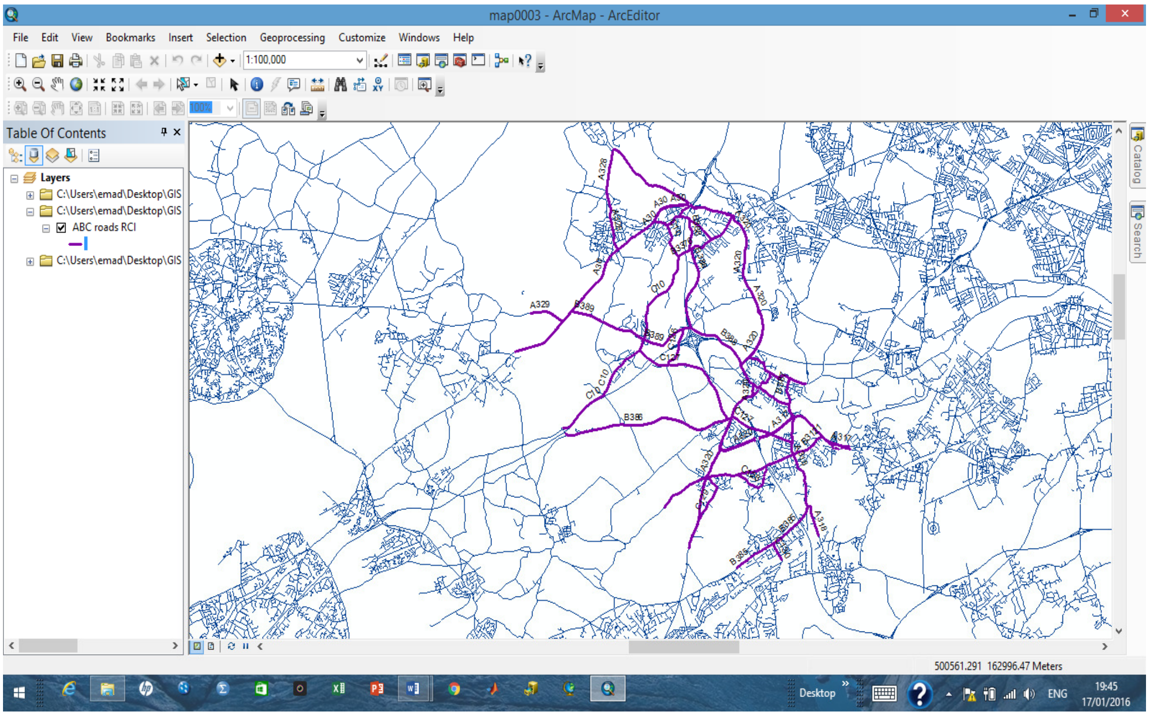


Figure 7.4: Base Map for Runnymede Roads

A30	A308	A317	A318	A319	A320	A328	A329	
B3121	B3376	B3407	B375	B385	B386	B387	B388	B389
C10	C125	C126	C127	C128	C129	C130	C229	

Table 7.1: Names of the Roads Used as Case Study

7.3 Case Studies for Testing the Proposed Model

7.3.1 Classifying and Describing Factors and Assigning Classification Scales

The 14 factors affecting pavement maintenance priority are used to compute the output priority scores for the proposed model. Therefore, classifying, describing factors and assigning classification scales are necessary. The tasks of classifying factors mainly followed the recommendation of the "Code of Practice for Highway Maintenance Management – Well-maintained Highways", Association of Directors of Environment, Economy, Planning and Transport (ADEPT) and Road Surface Treatments Association (RSTA) report, Adlinge & Gupta (2008) and various related reports, and assigning classification scales is scored by the researcher. However, some factors are also described and scored based on rational judgment.

As mentioned above, the scale of 1 to 3 is used for the assigned data in the priority matrix, where 1 represents least attention for pavement to be maintained, 2 represents intermediate attention for pavement to be maintained, and 3 represents immediate attention for pavement to be maintained. Classification scales for the 14 factors are shown in the tables given below:

<u>Remaining Service Life:</u>

ADEPT and RSTA had a nationally agreed baseline for pavement service life according to surface treatment. However, age of the pavement data availability would help in predicting the remaining service life.

Surface Treatment	Service Life	Scale
Surface Dressing: low to medium traffic	15 Years	1
Micro-surfacing	10 Years	2
Slurry Surfacing	6 Years	3
High Friction Surfacing	4 Years	

Table 7.2: Classification and Scale for the Remaining Service Life Factor. Source: (ADEPT and Raster, 2011) and Author Scaling

<u>Road Condition Indicator (RCI):</u>

The condition of the road network is reported nationally using a UK standard RCI, which is adopted by local road authorities, as it is concluded in the code of practice for highway maintenance management. The RCI takes account of four parameters: rutting, texture, longitudinal profile, and cracking.

In order to present the results graphically, a colour coding convention has been adopted using the traffic light system as follows:

<u>Green:</u> the road surface is generally in a good condition.

Amber: the road surface has some deterioration, hence, further investigation is needed to determine the best time for planned maintenance.

Red: the road surface is in a poor overall condition, hence, likely to require planned maintenance soon.

RCI	Colour Coding	Scale
≤ 40	Green	1
41 to 100	Amber	2
> 100	Red	3

Table 7.3: Classification and Scale for Road Condition Indicator RCI Factor. Source: (UK Roads Board, 2011) and Author Scaling

Type of Deterioration:

Deterioration Type	Description	Scale
Surface Defects	Repair the defect with a wearing course or an overlay	1
Disintegration	Area repairs or reconstruction may be required for extensive potholes	2
Cracking	Large areas of fatigue cracking require reclamation or reconstruction	
Surface Deformation	Reconstruction is required for extensive depression	3

Table 7.4: Classification and Scale for Type of Deterioration Factor. Source: (Aldinge & Gupta, 2008) and Author Scaling

Observed Deterioration Rate:

Pavement deteriorates over time, and the basic concept of deterioration rate is that the timing of maintenance actions can be greatly cost-effective, therefore extending the life for pavement.

Observed Deterioration Rate	Description	Scale
> 75% of Life	Condition very good	1
≤ 12% of Life	Very poor condition, it will cost more if delayed until this point	2
13% to 75% of Life	Condition fair, cost-effective if repaired at this point	3

Table 7.5: Classification and Scale for Observed Deterioration Rate Factor. Source: (VHB, 2012) and Author Scaling

Traffic Diversion:

Traffic Diversion	Scale
Traffic diversion required with potentially high environmental impact, high socio-economic impact, significantly increased journey length/time and high cost	1
Traffic Diversion required with minimum environmental impact, minimum socio-economic impact, minimum increased journey length/time and high cost	2
Traffic Diversion is not required or required with minimum or no environmental impact, minimum or no socio-economic impact, minimum or no increased journey length/time and minimum cost	3

Table 7.6: Classification and Scale for Traffic Diversion Factor (Ziad, 2009) Modified by the Author

Importance/Classification of Road:

The road importance represents the class of road.

<table>
<tr><th>Importance/Classification of Road</th><th>Description</th><th>Scale</th></tr>
<tr><td>Unclassified roads</td><td>Local roads intended for local traffic. The vast majority (60%) of roads in the UK fall within this category</td><td rowspan="2">1</td></tr>
<tr><td>Class C roads</td><td>Smaller roads intended to connect unclassified roads with A and B roads, and often linking a housing estate or a village to the rest of the network</td></tr>
<tr><td>Class B roads</td><td>Roads intended to connect different areas, and to feed traffic between A roads and smaller roads on the network</td><td>2</td></tr>
<tr><td>Class A roads</td><td>Major roads intended to provide large-scale transport links within or between areas</td><td>3</td></tr>
</table>

Table 7.7: Classification and Scale for Importance/Classification of Roads Factor. Source: (DfT, 2012) and Author Scaling

<u>Annual Average Daily Traffic (AADT):</u>

AADT represents the daily traffic volume.

Annual Average Daily Traffic (AADT)	Scale
< 10,000	1
10,000 to 50,000	2
> 50,000	3

Table 7.8: Classification and Scale for Annual Average Daily Traffic (AADT) Factor (Ziad,2009), Modified by the Author

Possible Conflict or Overlap with Other Road Works:

The aim of local road authorities is to maximise the life of any treatment on the road network. Therefore, coordinating with other road works including utilities is important.

Possible Conflict or Overlap with Other Road Works	Scale
There will be no other road works during the same period for planned maintenance	1
There will be minor other road works during the same period for planned maintenance	2
There will be major other road works during the same period for planned maintenance	3

Table 7.9: Classification and Scale for Possible Conflict or Overlap with Other Road Works Factor

Risk of Failure:

Risk of failure is judged according to the condition of the road.

Risk of Failure	Scale
Low or no risk of failure	1
Medium risk of failure	2
High risk of failure	3

Table 7.10: Classification and Scale for Risk of Failure Factor

Safety Concern:

Safety Concern	Scale
Low or no hazard to people and property	1
Intermediate hazard to people and property	2
Serious hazard that might be dangerous to public safety	3

Table 7.11: Classification and Scale for Safety Concern Factor

Accident Rate Related to Surface Condition:

Accident Rate Related to Surface Condition	Scale
Low accident rate	1
Medium accident rate	2
High accident rate	3

Table 7.12: Classification and Scale for Accident Rate Related to Surface Condition Factor

Scheme Cost:

The scheme cost represents the total all-inclusive cost of carrying out the maintenance work. According to the size of the scheme, the larger the scheme, the higher the cost will be.

Scheme Cost	Scale
Large maintenance scheme	1
Medium maintenance scheme	2
Small medium scheme	3

Table 7.13: Classification and Scale for Scheme Cost Factor

Available Funding:

Available funding is influencing the ability of efficiently maintaining the local road authorities' road network.

Available Funding	Scale
Funding is available to meet the minimum requirements for pavement maintenance	1
Funding is available to meet most of the requirements for pavement maintenance	2
Funding is available to meet all the requirements for pavement maintenance	3

Table 7.14: Classification and Scale for Available Funding Factor

Whole Life-cycle Cost:

Specialists agreed that the Whole Life-cycle Cost factor would be the highest priority, if sufficient funding were available for local road authorities. When investment decisions are based on the Whole Life-cycle Cost approach, local road authorities can demonstrate long-term value for money benefits.

The Whole Life-cycle cost is based on the analysis period, which represents the duration over which the maintenance costs are to be evaluated, and the discount rate, which is the technique that is used to compare costs that occur at different times (UK Roads Liaison Group, 2011).

Whole Life-cycle Cost		
Years	Discount Rate	Scale
0 to 30	3.5%	1
31 to 75	3.0%	2
76 to 125	2.5%	3

Table 7.15: Classification and Scale for Whole Life-cycle Cost Factor. Source: (UK Roads Liaison Group, 2011) and Author Scaling

7.3.2 Data Profiles of Alternative Roads

After scaling the factors affecting pavement maintenance according to the classification of each factor, scores of 1 to 3 have been assigned to each road representing the 14 factors, in order to form the priority matrix. However, due to difficulties to access real data for the case study (Runnymede roads), assumptions have been made regarding the scores to illustrate the calculations of the priority score. Table 7.16 shows the data profiles of alternative roads.

Road No.	Road Name	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
R1	A30	2	2	2	2	2	2	2	2	2	2	2	2	2	2
R2	A308	1	1	1	1	1	1	1	1	1	1	1	1	1	1
R3	A317	3	3	3	2	1	1	1	2	1	1	2	1	2	1
R4	A318	3	3	1	1	1	1	1	2	2	2	1	1	1	1
R5	A319	2	1	1	1	1	2	2	2	2	1	1	1	1	1
R6	A320	3	1	1	3	1	3	3	3	3	3	3	3	3	3
R7	A328	2	1	1	1	3	1	1	1	1	1	1	1	1	1
R8	A329	2	3	2	3	3	3	3	3	3	3	1	1	3	3
R9	B3121	1	1	1	1	1	3	1	1	1	1	1	1	2	1
R10	B3376	3	2	2	2	3	2	1	1	1	1	3	1	1	1
R11	B3407	2	1	1	3	1	1	1	1	1	1	1	2	1	1
R12	B375	3	3	3	3	3	3	3	3	3	3	3	3	3	3
R13	B385	1	1	1	1	1	3	1	1	1	1	1	2	1	1
R14	B386	2	1	1	1	3	1	1	1	1	1	1	2	1	1
R15	B387	3	3	3	3	3	3	3	3	3	3	2	2	2	1
R16	B388	1	1	1	1	1	1	1	1	1	1	1	2	1	1
R17	B389	2	3	3	3	2	2	2	2	1	1	1	1	1	1
R18	C10	3	3	3	3	3	3	3	3	3	3	3	1	1	1
R19	C125	1	1	1	1	1	1	1	1	1	1	1	1	1	1
R20	C126	1	1	2	2	3	3	3	3	3	2	2	2	2	2
R21	C127	2	1	1	1	1	1	1	1	1	1	3	1	1	1
R22	C128	1	1	1	1	1	3	2	1	1	1	1	1	1	1
R23	C129	3	3	2	2	2	2	3	3	3	3	3	3	3	3
R24	C130	2	2	2	2	2	2	2	2	2	1	1	1	1	1
R25	C229	1	1	1	1	1	1	3	3	3	1	1	1	1	1

Table 7.16: Profiles of Alternative Roads

7.3.3 Case Study for Pavement Maintenance Priority Score of Roads

The case study of Runnymede roads aims to test the practicability of the proposed model. The case study comprises 25 roads as shown in Table 7.16 above. Therefore, a PMPS for each alternative road has been calculated initially. Once the PMPS are obtained, a spreadsheet is designed indicating the PMPS values based on the score of individual factors. The following figures show the factors component of PMPS:

Figure 7.5 below shows PMPS component Remaining Service Life that has been calculated in accordance with the related score of factor mechanism, which is explained in section 7.3.1 for assigning a classification scale 1 to 3. Obtained scores for F_1 are multiplied with weight of factor value (in this case it is 0.077064) (see the first term in PMPS equation 7.1 for details). R3, R4, r6, R10, R12, R15, R18 and R23 achieved the highest scores equally, while R2, R9, R13, R16, R19, R20, R22 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F1	Roads	Score of Factor	PMPS - F1
R1	2	0.154128	R14	2	0.154128
R2	1	0.077064	R15	3	0.231192
R3	3	0.231192	R16	1	0.077064
R4	3	0.231192	R17	2	0.154128
R5	2	0.154128	R18	3	0.231192
R6	3	0.231192	R19	1	0.077064
R7	2	0.154128	R20	1	0.077064
R8	2	0.154128	R21	2	0.154128
R9	1	0.077064	R22	1	0.077064
R10	3	0.231192	R23	3	0.231192
R11	2	0.154128	R24	2	0.154128
R12	3	0.231192	R25	1	0.077064
R13	1	0.077064			

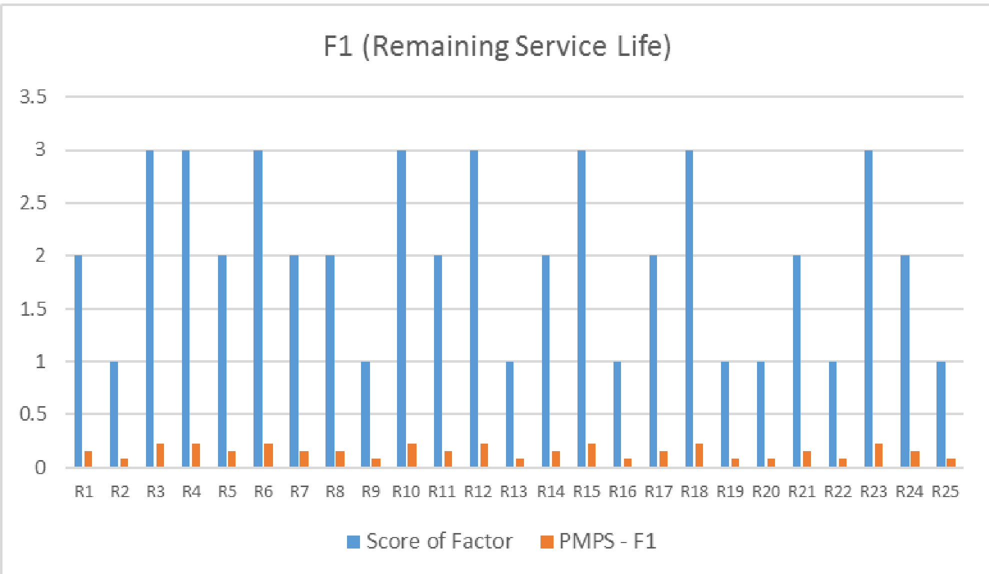


Figure 7.5: Remaining Service Life Component of PMPS

Figure 7.6 given below shows PMPS component RCI (Road Condition Indicator) that has been calculated in accordance with the score of factor. In order to solve the second term of equation 7.1, obtained scores for F_2 are multiplied with weight of factor value (in this case it is 0.071854). R3, R4, R8, R12, R15, R17, R18 and R23 achieved the highest scores equally, while R2, R5, R6, R7, R9, R11, R13, R14, R16, R19, R20, R21, R22 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F2	Roads	Score of Factor	PMPS - F2
R1	2	0.143708	R14	1	0.071854
R2	1	0.071854	R15	3	0.215562
R3	3	0.215562	R16	1	0.071854
R4	3	0.215562	R17	3	0.215562
R5	1	0.071854	R18	3	0.215562
R6	1	0.071854	R19	1	0.071854
R7	1	0.071854	R20	1	0.071854
R8	3	0.215562	R21	1	0.071854
R9	1	0.071854	R22	1	0.071854
R10	2	0.143708	R23	3	0.215562
R11	1	0.071854	R24	2	0.143708
R12	3	0.215562	R25	1	0.071854
R13	1	0.071854			

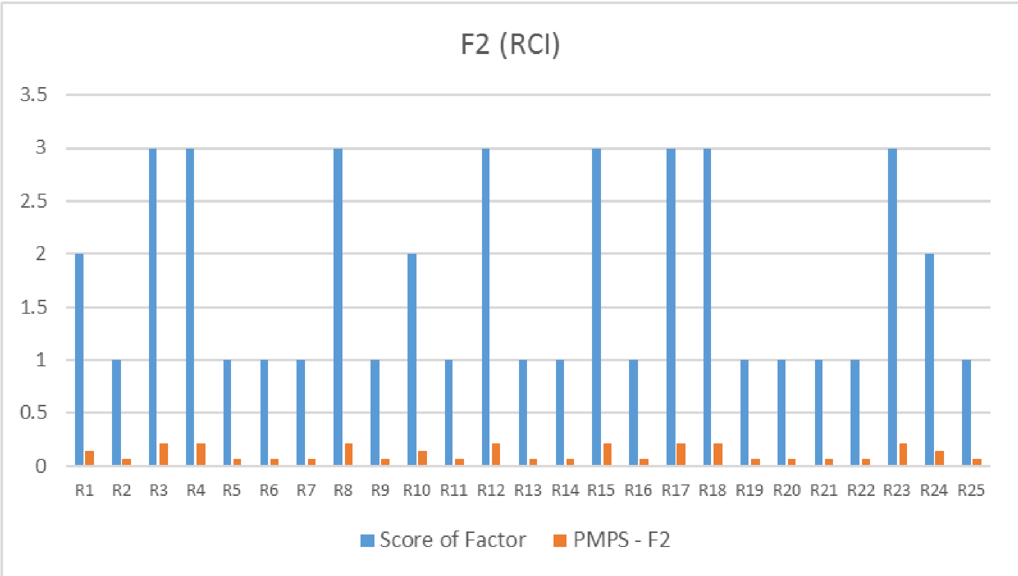


Figure 7.6: RCI Component of PMPS

Figure 7.7 given below shows PMPS component Type of Deterioration that has been calculated in accordance with the score of factor. In order to solve the third term of equation 7.1, obtained scores for F_3 are multiplied with weight of factor value (in this case it is 0.072606). R3, R12, R15, R17 and R18 achieved the highest scores equally, while R2, R4, R5, R6, R7, R9, R11, R13, R14, R16, R19, R21, R22 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F3	Roads	Score of Factor	PMPS - F3
R1	2	0.145212	R14	1	0.072606
R2	1	0.072606	R15	3	0.217818
R3	3	0.217818	R16	1	0.072606
R4	1	0.072606	R17	3	0.217818
R5	1	0.072606	R18	3	0.217818
R6	1	0.072606	R19	1	0.072606
R7	1	0.072606	R20	2	0.145212
R8	2	0.145212	R21	1	0.072606
R9	1	0.072606	R22	1	0.072606
R10	2	0.145212	R23	2	0.145212
R11	1	0.072606	R24	2	0.145212
R12	3	0.217818	R25	1	0.072606
R13	1	0.072606			

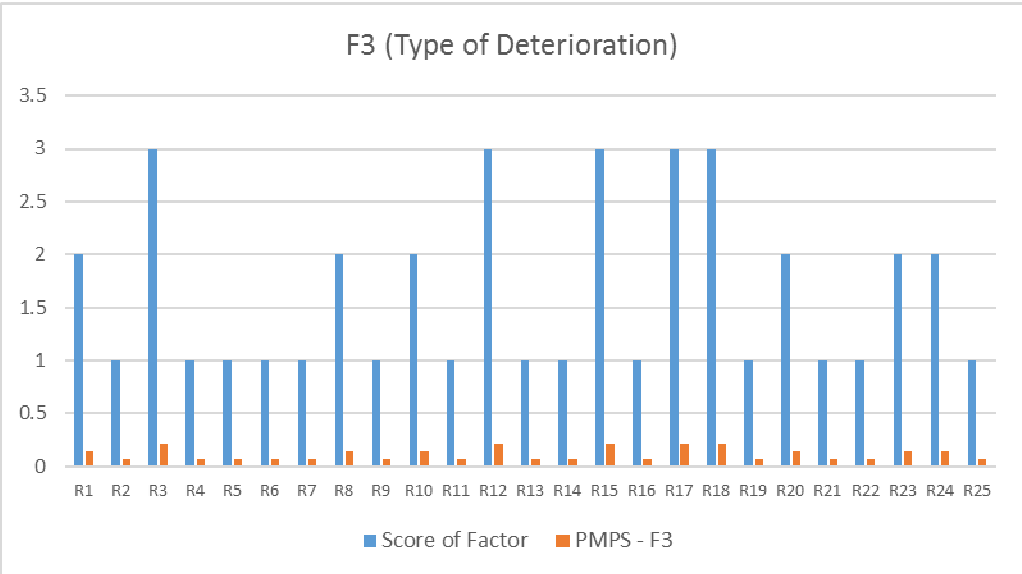


Figure 7.7: Type of Deterioration Component of PMPS

Figure 7.8 given below shows PMPS component Observed Deterioration Rate that has been calculated in accordance with the score of factor. In order to solve the fourth term of equation 7.1, obtained scores for F_4 are multiplied with weight of factor value (in this case it is 0.071317). R6, R8, R11, R12, R15, R17 and R18 achieved the highest scores equally, while R2, R4, R5, R7, R9, R13, R14, R16, R19, R21, R22 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F4	Roads	Score of Factor	PMPS - F4
R1	2	0.142634	R14	1	0.071317
R2	1	0.071317	R15	3	0.213951
R3	2	0.142634	R16	1	0.071317
R4	1	0.071317	R17	3	0.213951
R5	1	0.071317	R18	3	0.213951
R6	3	0.213951	R19	1	0.071317
R7	1	0.071317	R20	2	0.142634
R8	3	0.213951	R21	1	0.071317
R9	1	0.071317	R22	1	0.071317
R10	2	0.142634	R23	2	0.142634
R11	3	0.213951	R24	2	0.142634
R12	3	0.213951	R25	1	0.071317
R13	1	0.071317			

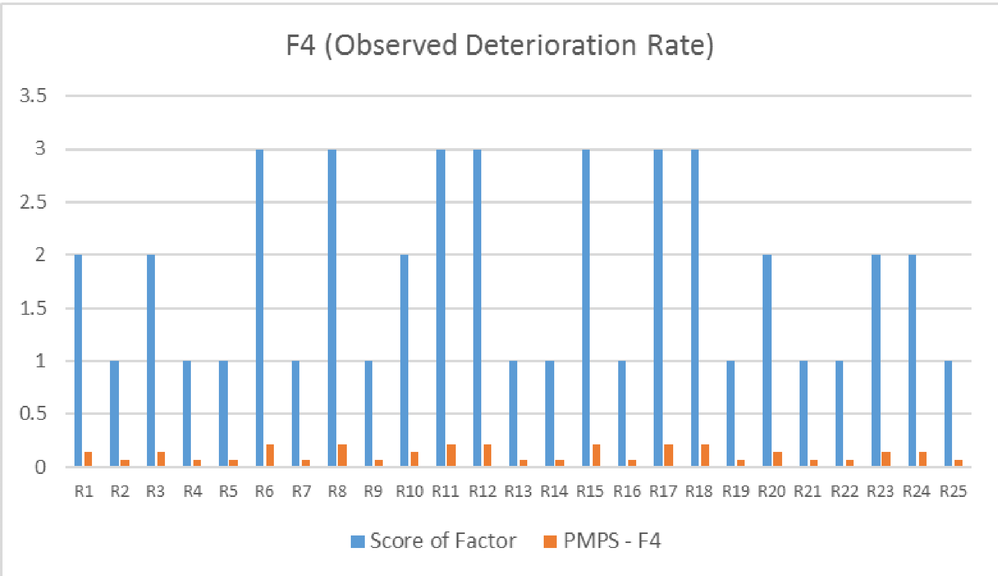


Figure 7.8: Observed Deterioration Rate Component of PMPS

Figure 7.9 given below shows PMPS component Traffic Diversion that has been calculated in accordance with the score of factor. In order to solve the fifth term of equation 7.1, obtained scores for F_5 are multiplied with weight of factor value (in this case it is 0.060899). R7, R8, R10, R12, R14, R15, R18 and R20 achieved the highest scores equally, while R2, R3, R4, R5, R6, R9, R11, R13, R16, R19, R21, R22 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F5	Roads	Score of Factor	PMPS - F5
R1	2	0.121798	R14	3	0.182697
R2	1	0.060899	R15	3	0.182697
R3	1	0.060899	R16	1	0.060899
R4	1	0.060899	R17	2	0.121798
R5	1	0.060899	R18	3	0.182697
R6	1	0.060899	R19	1	0.060899
R7	3	0.182697	R20	3	0.182697
R8	3	0.182697	R21	1	0.060899
R9	1	0.060899	R22	1	0.060899
R10	3	0.182697	R23	2	0.121798
R11	1	0.060899	R24	2	0.121798
R12	3	0.182697	R25	1	0.060899
R13	1	0.060899			

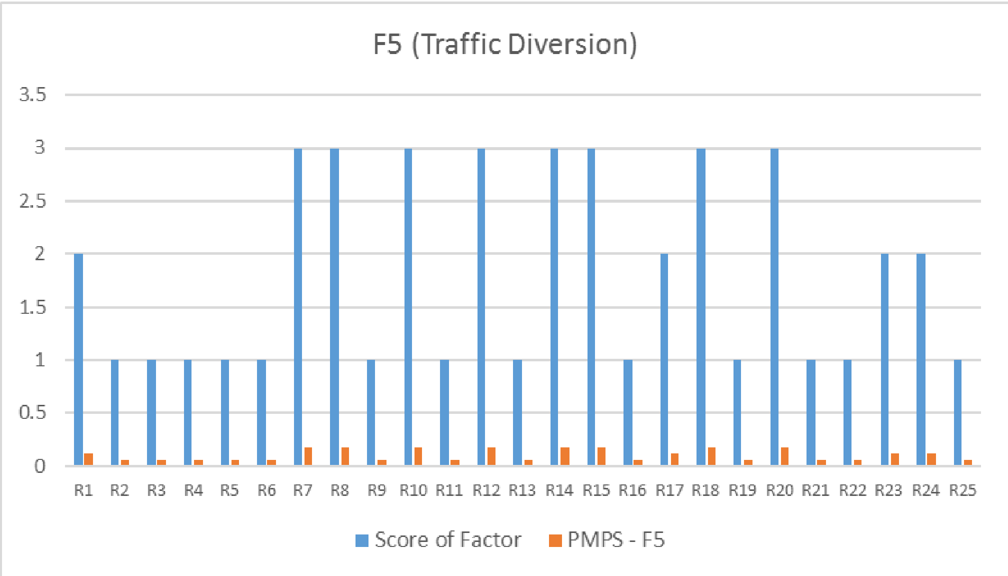


Figure 7.9: Traffic Diversion Component of PMPS

Figure 7.10 given below shows PMPS component Importance/Classification of Road that has been calculated in accordance with the score of factor. In order to solve the sixth term of equation 7.1, obtained scores for F_6 are multiplied with weight of factor value (in this case it is 0.078191). R6, R8, R9, R12, R13, R15, R18, R20 and R22 achieved the highest scores equally, while R2, R3, R4, R7, R11, R14, R16, R19, R21 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F6	Roads	Score of Factor	PMPS - F6
R1	2	0.156382	R14	1	0.078191
R2	1	0.078191	R15	3	0.234573
R3	1	0.078191	R16	1	0.078191
R4	1	0.078191	R17	2	0.156382
R5	2	0.156382	R18	3	0.234573
R6	3	0.234573	R19	1	0.078191
R7	1	0.078191	R20	3	0.234573
R8	3	0.234573	R21	1	0.078191
R9	3	0.234573	R22	3	0.234573
R10	2	0.156382	R23	2	0.156382
R11	1	0.078191	R24	2	0.156382
R12	3	0.234573	R25	1	0.078191
R13	3	0.234573			

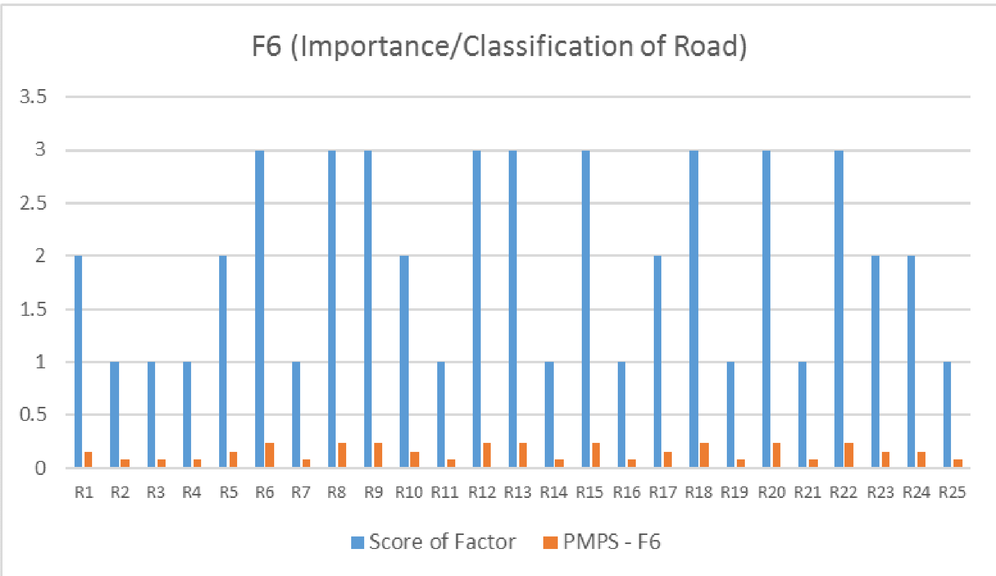


Figure 7.10: Importance/Classification of Road Component of PMPS

Figure 7.11 given below shows PMPS component AADT (Annual Average Daily Traffic) that has been calculated in accordance with the score of factor. In order to solve the seventh term of equation 7.1, obtained scores for F_7 are multiplied with weight of factor value (in this case it is 0.05961). R6, R8, R12, R15, R18, R20, R23 and R25 achieved the highest scores equally, while R2, R3, R4, R7, R9, R10, R11, R13, R14, R16, R19 and R21 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F7	Roads	Score of Factor	PMPS - F7
R1	2	0.11922	R14	1	0.05961
R2	1	0.05961	R15	3	0.17883
R3	1	0.05961	R16	1	0.05961
R4	1	0.05961	R17	2	0.11922
R5	2	0.11922	R18	3	0.17883
R6	3	0.17883	R19	1	0.05961
R7	1	0.05961	R20	3	0.17883
R8	3	0.17883	R21	1	0.05961
R9	1	0.05961	R22	2	0.11922
R10	1	0.05961	R23	3	0.17883
R11	1	0.05961	R24	2	0.11922
R12	3	0.17883	R25	3	0.17883
R13	1	0.05961			

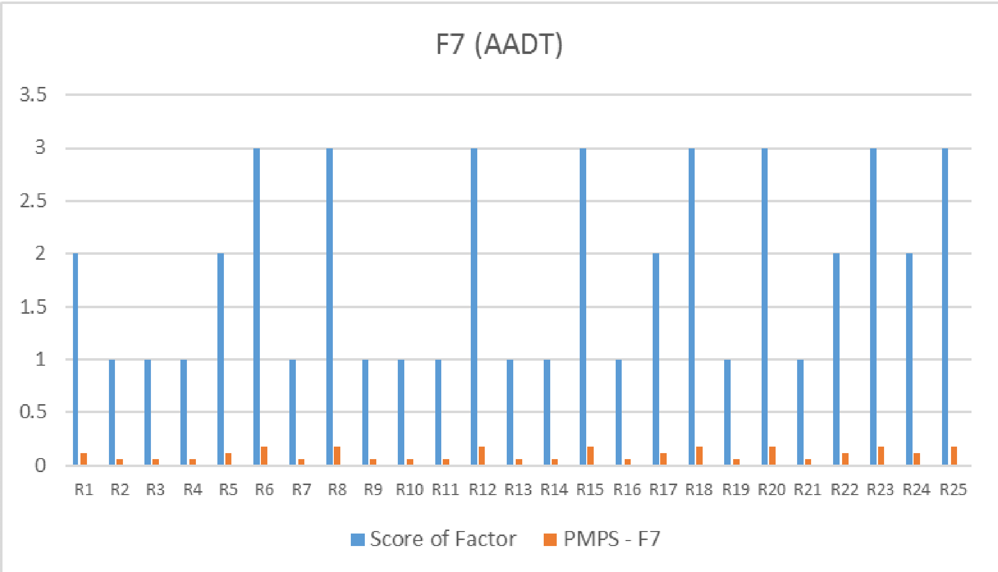


Figure 7.11: AADT Component of PMPS

Figure 7.12 given below shows PMPS component Possible Conflict or Overlap with Other Road Works that has been calculated in accordance with the score of factor. In order to solve the eighth term of equation 7.1, obtained scores for F_8 are multiplied with weight of factor value (in this case it is 0.069089). R6, R8, R12, R15, R18, R20, R23 and R25 achieved the highest scores equally, while R2, R7, R9, R10, R11, R13, R14, R16, R19, R21 and R22 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F8	Roads	Score of Factor	PMPS - F8
R1	2	0.138178	R14	1	0.069089
R2	1	0.069089	R15	3	0.207267
R3	2	0.138178	R16	1	0.069089
R4	2	0.138178	R17	2	0.138178
R5	2	0.138178	R18	3	0.207267
R6	3	0.207267	R19	1	0.069089
R7	1	0.069089	R20	3	0.207267
R8	3	0.207267	R21	1	0.069089
R9	1	0.069089	R22	1	0.069089
R10	1	0.069089	R23	3	0.207267
R11	1	0.069089	R24	2	0.138178
R12	3	0.207267	R25	3	0.207267
R13	1	0.069089			

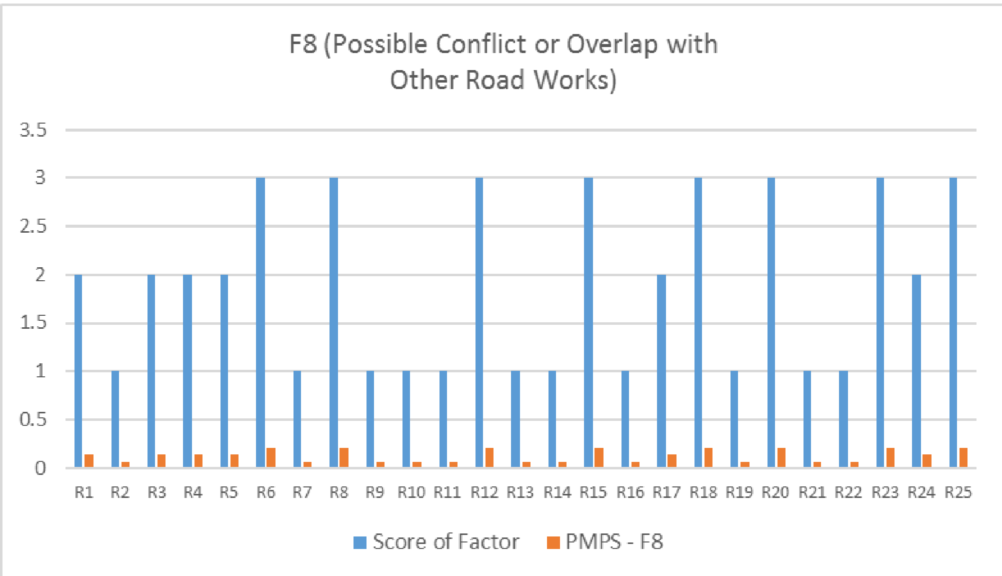


Figure 7.12: Possible Conflict or Overlap with Other Road Works Component of PMPS

Figure 7.13 given below shows PMPS component Risk of Failure that has been calculated in accordance with the score of factor. In order to solve the ninth term of equation 7.1, obtained scores for F_9 are multiplied with weight of factor value (in this case it is 0.072042). R6, R8, R12, R15, R18, R20, R23 and R25 achieved the highest scores equally, while R2, R3, R7, R9, R10, R11, R13, R14, R16, R17, R19, R21 and R22 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F9	Roads	Score of Factor	PMPS - F9
R1	2	0.144084	R14	1	0.072042
R2	1	0.072042	R15	3	0.216126
R3	1	0.072042	R16	1	0.072042
R4	2	0.144084	R17	1	0.072042
R5	2	0.144084	R18	3	0.216126
R6	3	0.216126	R19	1	0.072042
R7	1	0.072042	R20	3	0.216126
R8	3	0.216126	R21	1	0.072042
R9	1	0.072042	R22	1	0.072042
R10	1	0.072042	R23	3	0.216126
R11	1	0.072042	R24	2	0.144084
R12	3	0.216126	R25	3	0.216126
R13	1	0.072042			

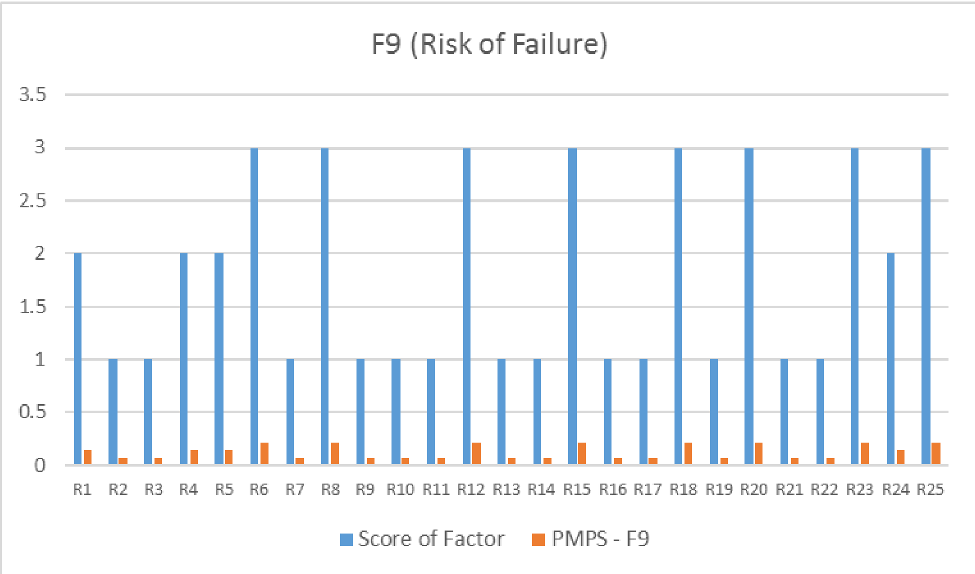


Figure 7.13: Risk of Failure Component of PMPS

Figure 7.14 given below shows PMPS component Safety Concern that has been calculated in accordance with the score of factor. In order to solve the tenth term of equation 7.1, obtained scores for F_{10} are multiplied with weight of factor value (in this case it is 0.080044). R6, R8, R12, R15, R18 and R23 achieved the highest scores equally, while R2, R3, R5, R7, R9, R10, R11, R13, R14, R16, R17, R19, R21, R22, R24 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F10	Roads	Score of Factor	PMPS - F10
R1	2	0.160088	R14	1	0.080044
R2	1	0.080044	R15	3	0.240132
R3	1	0.080044	R16	1	0.080044
R4	2	0.160088	R17	1	0.080044
R5	1	0.080044	R18	3	0.240132
R6	3	0.240132	R19	1	0.080044
R7	1	0.080044	R20	2	0.160088
R8	3	0.240132	R21	1	0.080044
R9	1	0.080044	R22	1	0.080044
R10	1	0.080044	R23	3	0.240132
R11	1	0.080044	R24	1	0.080044
R12	3	0.240132	R25	1	0.080044
R13	1	0.080044			

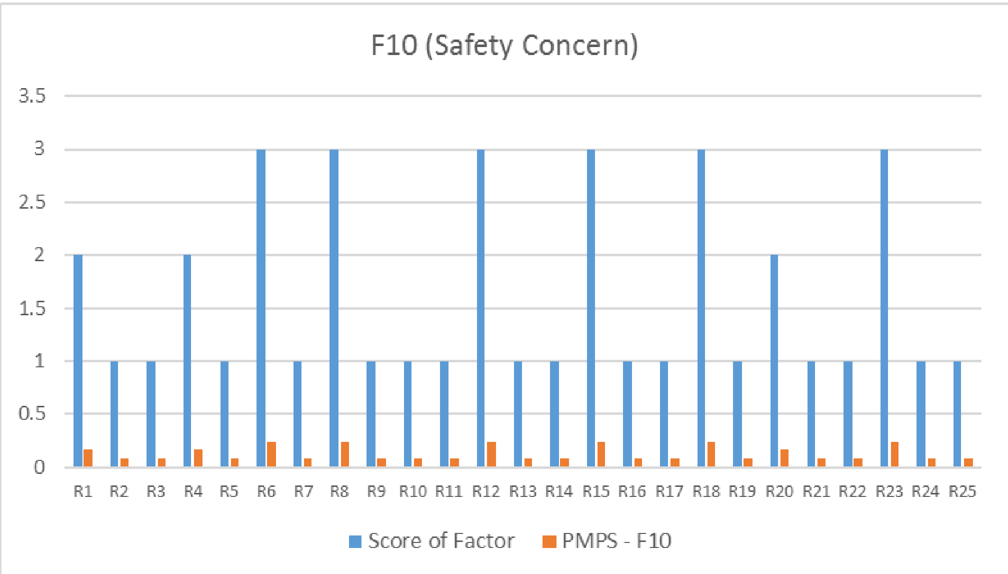


Figure 7.14: Safety Concern Component of PMPS

Figure 7.15 given below shows PMPS component Accident Rate Related to Surface Condition that has been calculated in accordance with the score of factor. In order to solve the eleventh term of equation 7.1, obtained scores for F_{11} are multiplied with weight of factor value (in this case it is 0.073546). R6, R10, R12, R18, R21 and R23 achieved the highest scores equally, while R2, R4, R5, R7, R8, R9, R11, R13, R14, R16, R17, R19, R22, R24 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F11	Roads	Score of Factor	PMPS - F11
R1	2	0.147092	R14	1	0.073546
R2	1	0.073546	R15	2	0.147092
R3	2	0.147092	R16	1	0.073546
R4	1	0.073546	R17	1	0.073546
R5	1	0.073546	R18	3	0.220638
R6	3	0.220638	R19	1	0.073546
R7	1	0.073546	R20	2	0.147092
R8	1	0.073546	R21	3	0.220638
R9	1	0.073546	R22	1	0.073546
R10	3	0.220638	R23	3	0.220638
R11	1	0.073546	R24	1	0.073546
R12	3	0.220638	R25	1	0.073546
R13	1	0.073546			

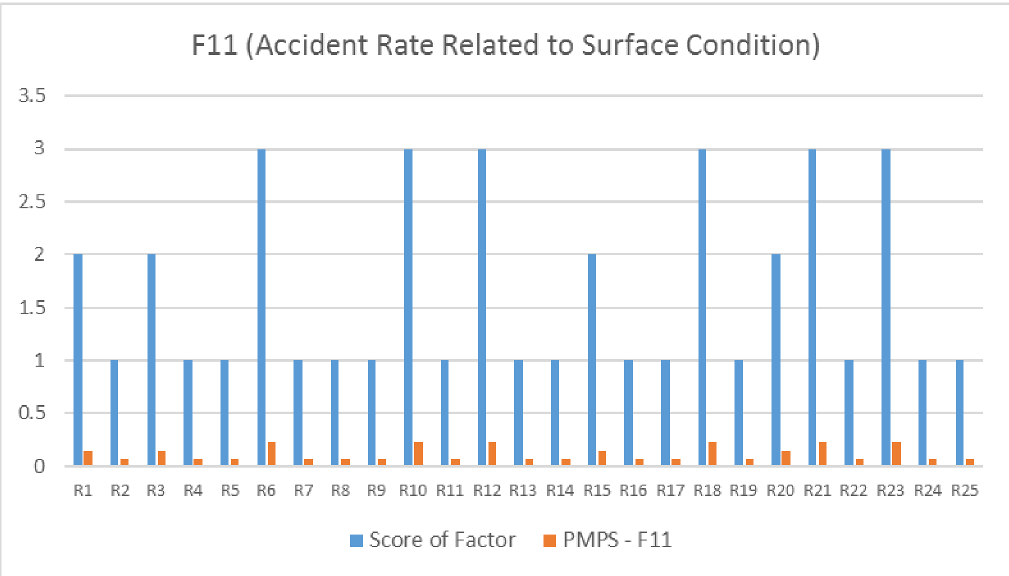


Figure 7.15: Accident Rate Related to Surface Condition Component of PMPS

Figure 7.16 given below shows PMPS component Scheme Cost that has been calculated in accordance with the score of factor. In order to solve the twelfth term of equation 7.1, obtained scores for F_{12} are multiplied with weight of factor value (in this case it is 0.060738). R6, R12, and R23 achieved the highest scores equally, while R2, R3, R4, R5, R7, R8, R9, R10, R17, R18, R19, R21, R22, R24 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F12	Roads	Score of Factor	PMPS - F12
R1	2	0.121476	R14	2	0.121476
R2	1	0.060738	R15	2	0.121476
R3	1	0.060738	R16	2	0.121476
R4	1	0.060738	R17	1	0.060738
R5	1	0.060738	R18	1	0.060738
R6	3	0.182214	R19	1	0.060738
R7	1	0.060738	R20	2	0.121476
R8	1	0.060738	R21	1	0.060738
R9	1	0.060738	R22	1	0.060738
R10	1	0.060738	R23	3	0.182214
R11	2	0.121476	R24	1	0.060738
R12	3	0.182214	R25	1	0.060738
R13	2	0.121476			

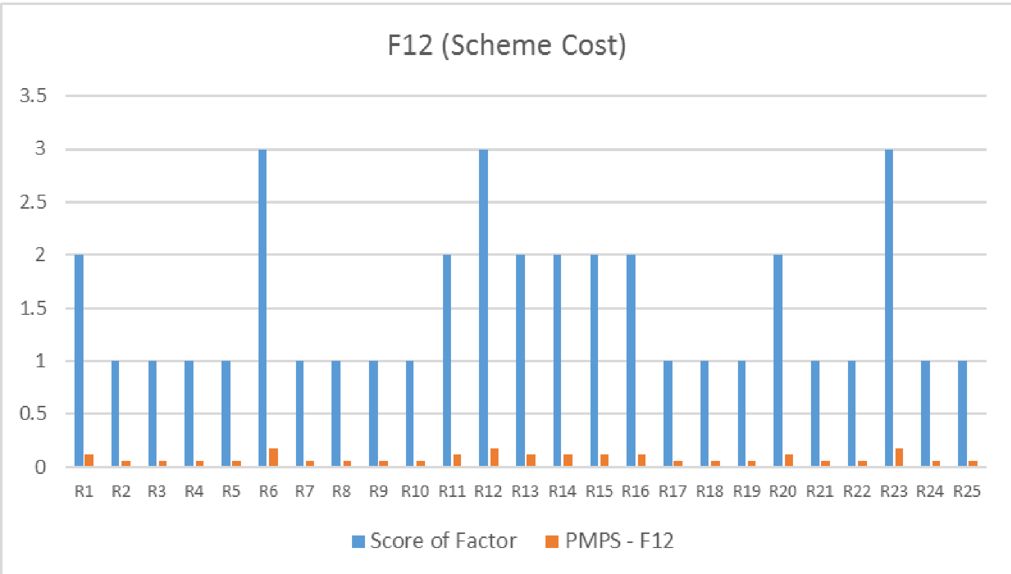


Figure 7.16: Scheme Cost Component of PMPS

Figure 7.17 given below shows PMPS component Available Funding that has been calculated in accordance with the score of factor. In order to solve the thirteenth term of equation 7.1, obtained scores for F_{13} are multiplied with weight of factor value (in this case it is 0.083186). R6, R8, R12, and R23 achieved the highest scores equally, while R2, R4, R5, R7, R10, R11, R13, R14, R16, R17, R18, R19, R21, R22, R24 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F13	Roads	Score of Factor	PMPS - F13
R1	2	0.166372	R14	1	0.083186
R2	1	0.083186	R15	2	0.166372
R3	2	0.166372	R16	1	0.083186
R4	1	0.083186	R17	1	0.083186
R5	1	0.083186	R18	1	0.083186
R6	3	0.249558	R19	1	0.083186
R7	1	0.083186	R20	2	0.166372
R8	3	0.249558	R21	1	0.083186
R9	2	0.166372	R22	1	0.083186
R10	1	0.083186	R23	3	0.249558
R11	1	0.083186	R24	1	0.083186
R12	3	0.249558	R25	1	0.083186
R13	1	0.083186			

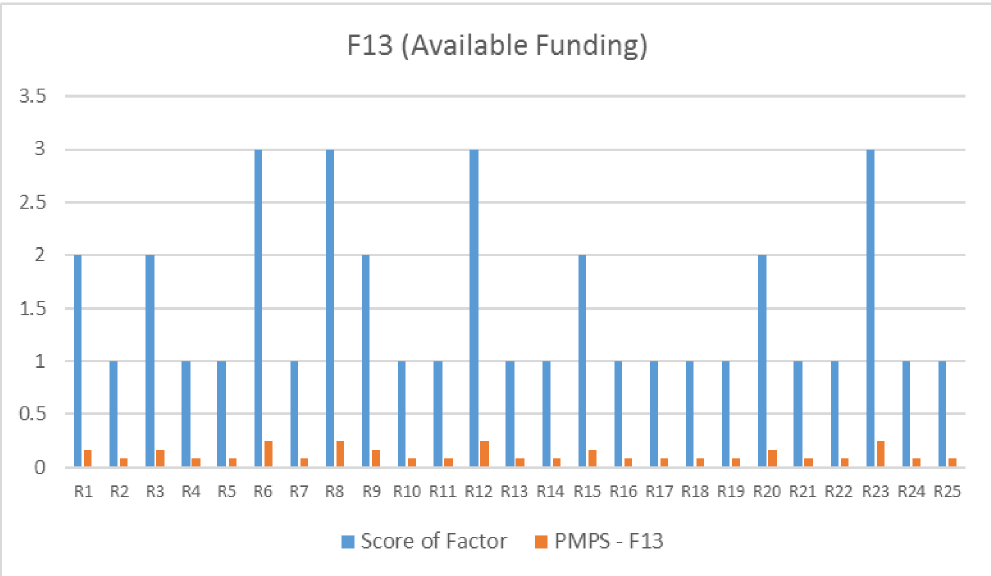


Figure 7.17: Available Funding Component of PMPS

Figure 7.18 given below shows PMPS component Whole Life-cycle Cost that has been calculated in accordance with the score of factor. In order to solve the fourteenth term of equation 7.1, obtained scores for F_{14} are multiplied with weight of factor value (in this case it is 0.069814). R6, R8, R12, and R23 achieved the highest scores equally, while R2, R3, R4, R5, R7, R9, R10, R11, R13, R14, R15, R16, R17, R18, R19, R21, R22, R24 and R25 achieved the lowest scores equally.

Roads	Score of Factor	PMPS - F14
R1	2	0.139628
R2	1	0.069814
R3	1	0.069814
R4	1	0.069814
R5	1	0.069814
R6	3	0.209442
R7	1	0.069814
R8	3	0.209442
R9	1	0.069814
R10	1	0.069814
R11	1	0.069814
R12	3	0.209442
R13	1	0.069814
R14	1	0.069814
R15	1	0.069814
R16	1	0.069814
R17	1	0.069814
R18	1	0.069814
R19	1	0.069814
R20	2	0.139628
R21	1	0.069814
R22	1	0.069814
R23	3	0.209442
R24	1	0.069814
R25	1	0.069814

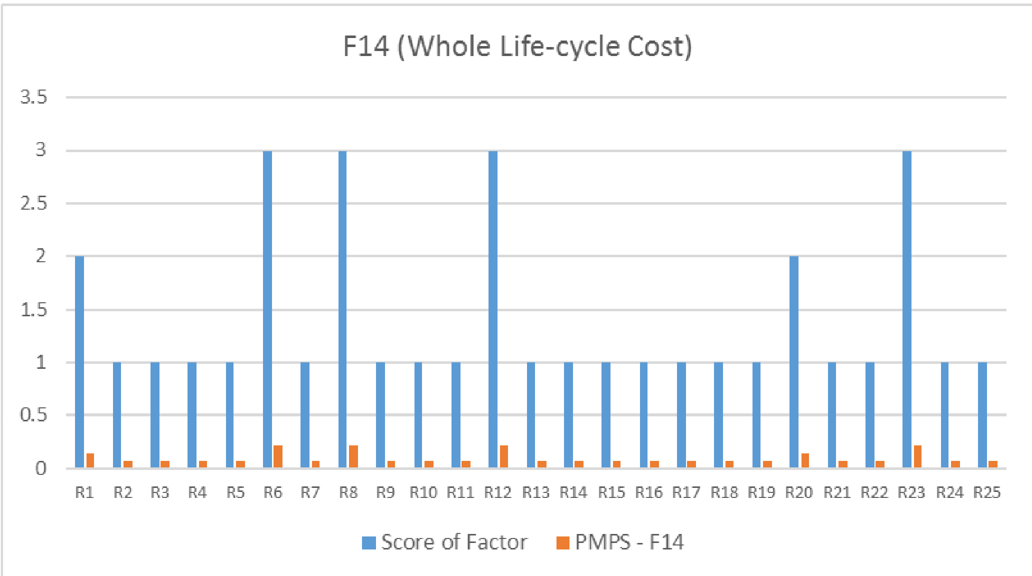


Figure 7.18: Whole Life-cycle Cost Component of PMPS

7.3.4 Solving Pavement Maintenance Priority Score (PMPS) Equation

The abovementioned figures illustrate individual component scores. In order to achieve the overall PMPS, the PMPS equation should be solved. The PMPS equation can be represented as follows:

$$PMPS = [(F_1 * W_1) + (F_2 * W_2) + (F_3 * W_3) + (F_4 * W_4) + (F_5 * W_5) + (F_6 * W_6) + (F_7 * W_7) + (F_8 * W_8) + (F_9 * W_9) + (F_{10} * W_{10}) + (F_{11} * W_{11}) + (F_{12} * W_{12}) + (F_{13} * W_{13}) + (F_{14} * W_{14})] \qquad (7.2)$$

Where,

F = Score of Factor

W = Weight of Factor

PMPS equation 7.2 has been calculated in Excel software in order to integrate the spreadsheet into ArcGIS software with the GIS base map layer of Runnymede roads shown earlier in Figure 7.4 based on Road Name. Figures 7.19 and 7.20 below illustrate the calculation of overall PMPS and the distribution of alternative roads respectively.

Road No.	Road Name	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
R1	A30	2	2	2	2	2	2	2	2	2	2	2	2	2	2
R2	A308	1	1	1	1	1	1	1	1	1	1	1	1	1	1
R3	A317	3	3	3	2	1	1	1	2	1	1	2	1	2	1
R4	A318	3	3	1	1	1	1	1	2	2	2	1	1	1	1
R5	A319	2	1	1	1	1	2	2	2	2	1	1	1	1	1
R6	A320	3	1	1	3	1	3	3	3	3	3	3	3	3	3
R7	A328	2	1	1	1	3	1	1	1	1	1	1	1	1	1
R8	A329	2	3	2	3	3	3	3	3	3	3	1	1	3	3
R9	B3121	1	1	1	1	1	3	1	1	1	1	1	1	2	1
R10	B3376	3	2	2	2	3	2	1	1	1	1	3	1	1	1
R11	B3407	2	1	1	3	1	1	1	1	1	1	1	2	1	1
R12	B375	3	3	3	3	3	3	3	3	3	3	3	3	3	3
R13	B385	1	1	1	1	1	3	1	1	1	1	1	2	1	1
R14	B386	2	1	1	1	3	1	1	1	1	1	1	2	1	1
R15	B387	3	3	3	3	3	3	3	3	3	3	2	2	2	1
R16	B388	1	1	1	1	1	1	1	1	1	1	1	2	1	1
R17	B389	2	3	3	3	2	2	2	2	1	1	1	1	1	1
R18	C10	3	3	3	3	3	3	3	3	3	3	3	1	1	1
R19	C125	1	1	1	1	1	1	1	1	1	1	1	1	1	1
R20	C126	1	1	2	2	3	3	3	3	3	2	2	2	2	2
R21	C127	2	1	1	1	1	1	1	1	1	1	3	1	1	1
R22	C128	1	1	1	1	1	3	2	1	1	1	1	1	1	1
R23	C129	3	3	2	2	2	2	3	3	3	3	3	3	3	3
R24	C130	2	2	2	2	2	2	2	2	2	1	1	1	1	1
R25	C229	1	1	1	1	1	1	3	3	3	1	1	1	1	1

x

Weights
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0.071854
0.072606
0.071317
0.060899
0.078191
0.059610
0.069089
0.072042
0.080044
0.073546
0.060738
0.083186
0.069814

=

PMPS
2.000000
1.000000
1.740186
1.519011
1.355996
2.589282
1.198862
2.581762
1.239568
1.716986
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1.259600
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1.776407
2.572524
1.000000
2.190913
1.224156
1.215992
2.716987
1.632672
1.401482

Figure 7.19: Calculation of Overall PMPS

Road No.	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	PMPS
R1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.000000
R2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.000000
R3	3	3	3	2	1	1	1	2	1	1	2	1	2	1	1.740186
R4	3	3	1	1	1	1	1	2	2	2	1	1	1	1	1.519011
R5	2	1	1	1	1	2	2	2	2	1	1	1	1	1	1.355996
R6	3	1	1	3	1	3	3	3	3	3	3	3	3	3	2.589282
R7	2	1	1	1	3	1	1	1	1	1	1	1	1	1	1.198862
R8	2	3	2	3	3	3	3	3	3	3	1	1	3	3	2.581762
R9	1	1	1	1	1	3	1	1	1	1	1	1	2	1	1.239568
R10	3	2	2	2	3	2	1	1	1	1	3	1	1	1	1.716986
R11	2	1	1	3	1	1	1	1	1	1	1	2	1	1	1.280436
R12	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3.000000
R13	1	1	1	1	1	3	1	1	1	1	1	2	1	1	1.217120
R14	2	1	1	1	3	1	1	1	1	1	1	2	1	1	1.259600
R15	3	3	3	3	3	3	3	3	3	3	2	2	2	1	2.642902
R16	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1.060738
R17	2	3	3	3	2	2	2	2	1	1	1	1	1	1	1.776407
R18	3	3	3	3	3	3	3	3	3	3	3	1	1	1	2.572524
R19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.000000
R20	1	1	2	2	3	3	3	3	3	2	2	2	2	2	2.190913
R21	2	1	1	1	1	1	1	1	1	1	3	1	1	1	1.224156
R22	1	1	1	1	1	3	2	1	1	1	1	1	1	1	1.215992
R23	3	3	2	2	2	2	3	3	3	3	3	3	3	3	2.716987
R24	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1.632672
R25	1	1	1	1	1	1	3	3	3	1	1	1	1	1	1.401482

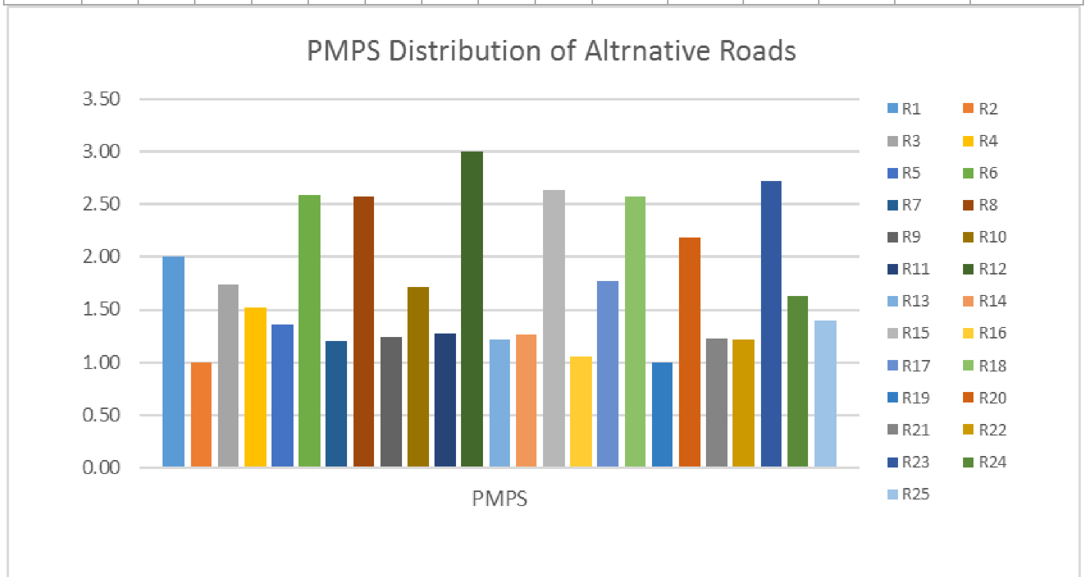

Figure 7.20: PMPS Distribution of Roads

The features of ArcGIS 10 software have been used to combine the data in Figure 7.19 with data in the attribute table of the base map of the Runnymede roads layer. Priority values have been classified into 3 classes using the Symbology feature and natural breaks is selected with three colours to represent each class. The prioritised roads are shown in Figure 7.21 below.

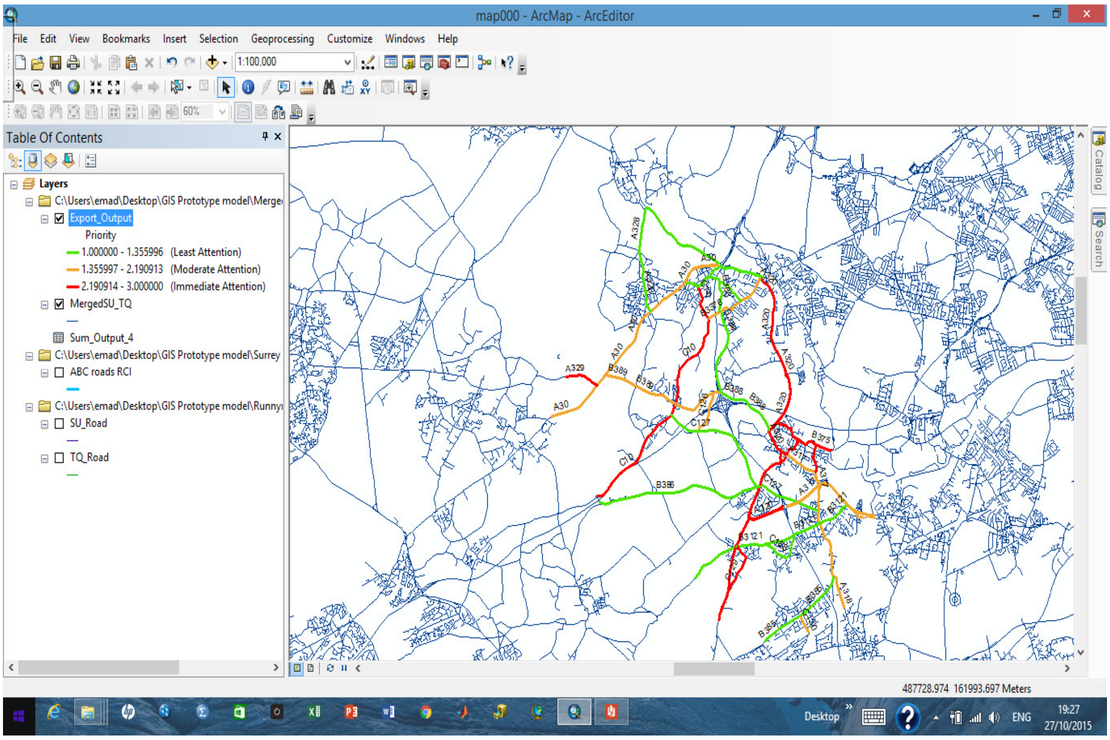

Figure 7.21: Classified Maintenance Priority for Roads in GIS

Red coloured roads indicate to an immediate action required for maintenance, where roads A320, A329, B375, B387, C10 and C129 achieved the highest PMPS of 2.589282, 2.581762, 3.0, 2.642902, 2.572524 and 2.716987 respectively.

Amber coloured roads indicate to a moderate action required for maintenance, where roads A30, A317, A318, B389, B3376, C126, C130 and C229 achieved the medium PMPS of 2.0, 1.740186, 1.519011, 1.776407, 1.716986, 2.190913, 1.632672 and 1.401482 respectively.

Green coloured roads indicate to least action required for maintenance, where roads A308, A319, A328, B3121, B3407, B385, B386, B388, C125, C127 and C128 achieved the lowest PMPS of 1.0, 1.355996, 1.198862, 1.239568, 1.280432, 1.217120, 1.2596, 1.060739, 1.0, 1.224156 and 1.215992 respectively.

In order to visualise each road in accordance with its priority score, priority values are classified into 23 classes as in two occasions two different roads achieved the same priority score value (R2 and R19). Figure 7.22 shows the 25 roads with a colour scheme where the darkest colour represents the highest PMPS and the lightest colour represents the lowest PMPS.

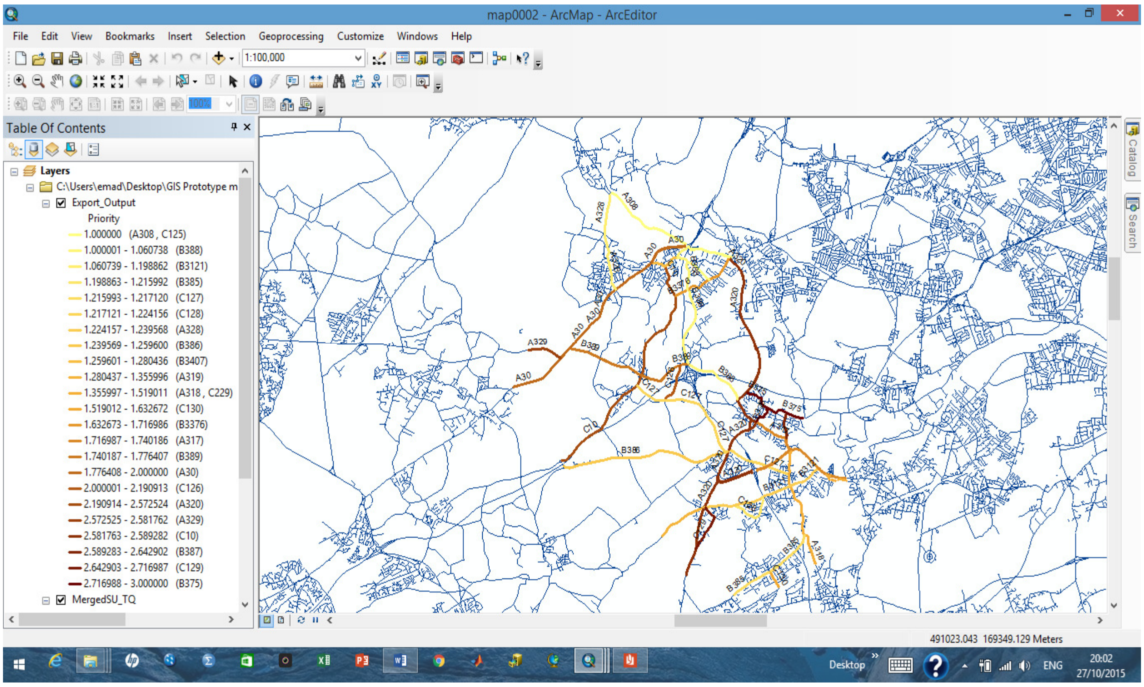

Figure 7.22: PMPS for Roads in GIS

7.3.5 Ranking of Alternative Roads

The given PMPS equation is a representation of the priority of roads regarding pavement maintenance. Higher scores indicate higher need for pavement maintenance. The highest priority of Runnymede roads is R12 (B375), and the lowest priority is R2 (A308) and R19 (C125). In order to visualise and demonstrate the ranking of the 25 roads concluded in the case study, a GIS analysis has been performed. Therefore, ranking of roads is visualised in the GIS map according to their colour, and ranking is also illustrated in the GIS table of content on the left of the map as shown in Figure 7.23 below. Also, extracted results from the GIS map are illustrated in Table 7.17.

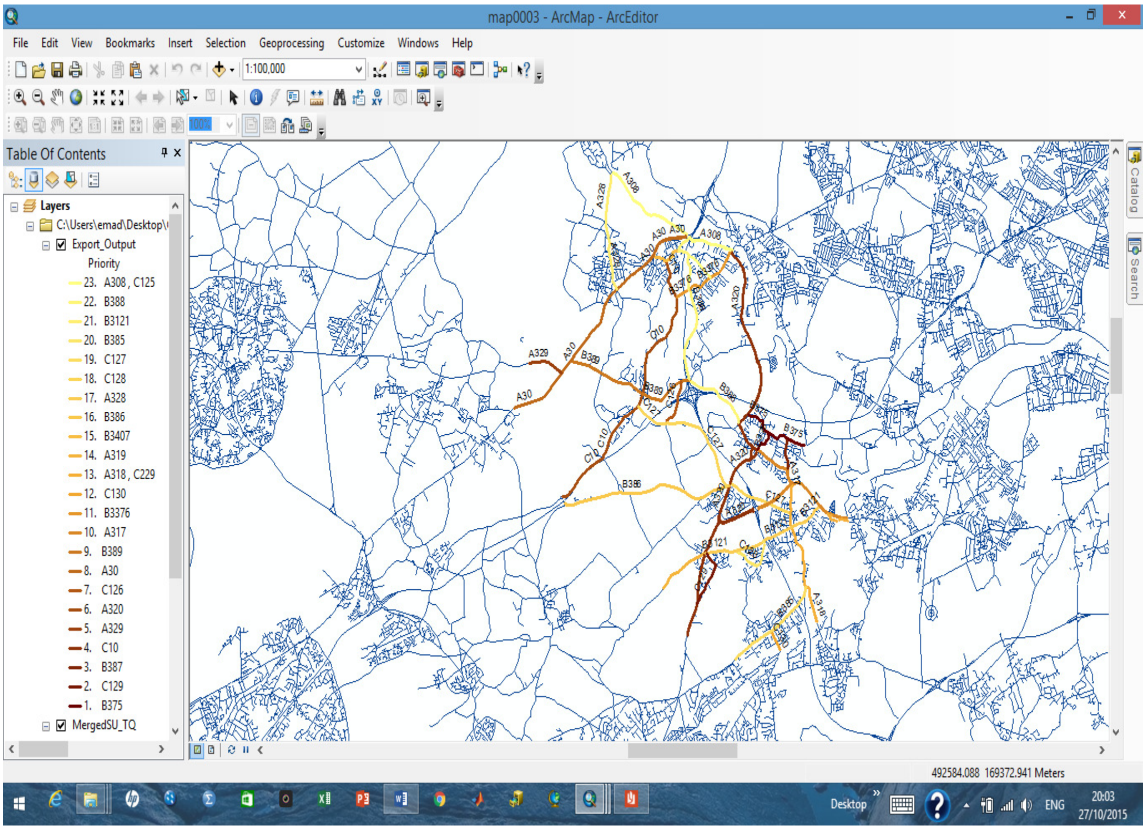

Figure 7.23: Ranking of Roads in GIS

Road No.	Road Name	Range of PMPS	Ranking of Roads
R12	B375	2.716988 - 3.000000	**1**
R23	C129	2.642903 - 2.716987	**2**
R15	B387	2.589283 - 2.642902	**3**
R18	C10	2.581763 - 2.589282	**4**
R8	A329	2.572525 - 2.581762	**5**
R6	A320	2.190914 - 2.572524	**6**
R20	C126	2.000001 - 2.190913	**7**
R1	A30	1.776408 - 2.000000	**8**
R17	B389	1.740187 - 1.776407	**9**
R3	A317	1.716987 - 1.740186	**10**
R10	B3376	1.632673 - 1.716986	**11**
R24	C130	1.519012 - 1.632672	**12**
R4, R25	A318, C229	1.355997 - 1.519011	**13**
R5	A319	1.280437 - 1.355996	**14**
R11	B3407	1.259601 - 1.280436	**15**
R14	B386	1.239569 - 1.259600	**16**
R7	A328	1.224157 - 1.239568	**17**
R22	C128	1.217121 - 1.224156	**18**
R21	C127	1.215993 - 1.217120	**19**
R13	B385	1.198863 - 1.215992	**20**
R9	B3121	1.060739 - 1.198862	**21**
R16	B388	1.000001 - 1.060738	**22**
R2, R19	A308, C125	1.000000	**23**

Table 7.17: Ranking of Roads

7.4 Sensitivity Analysis

The sensitivity analysis is determining the sensitivity of the most influential parameters on model results. When developing decision support systems using multiple criteria decision making methods, it is important to perform sensitivity analysis for these methods (Simanaviciene and Ustinovichius, 2010). The sensitivity methods include the following: variation of inputs by one standard deviation and by 20%, partial derivatives, an importance index, a sensitivity index, a relative derivation ratio, a relative derivation of the output distribution, standardized regression coefficients, partial rank correlation coefficient, rank regression coefficient, the Cramer-von Mises test, the Smirnov test, the squared-ranks test, and the Mann-Whitney test (Hamby, 1994; hamby, 1995; Pannell, 1997; Saltelli et al., 2004).

For this research, the Sensitivity Index (SI) is chosen as the sensitivity analysis method to be used for parameters. SI is the simple method proposed by Hoffman and Gardner (1983) that is used for determining the sensitivity of results to different parameters of the model by calculating the output percent difference when varying one input parameter from its minimum value to its maximum value as follows (Hamby, 1995; Pannell, 1997):

$$SI = (D_{max} - D_{min})/D_{max} \tag{7.3}$$

where D_{max} is the output result when the parameter in equation is set at its maximum value and D_{min} is the result for the minimum parameter value.

SI is applied to examine the sensitivity of parameters for R12 (B37). Figures 7.24a and 7.24b below show the results of SI for R12 in the PMPS equation.

Factor	Dmax	Dmin	Dmax - Dmin	SI = (Dmax-Dmin)/Dmax
F1	3.000000	2.845872	0.154128	0.051376
F2	3.000000	2.856292	0.143708	0.047903
F3	3.000000	2.854788	0.145212	0.048404
F4	3.000000	2.857366	0.142634	0.047545
F5	3.000000	2.878202	0.121798	0.040599
F6	3.000000	2.843618	0.156382	0.052127
F7	3.000000	2.88078	0.11922	0.03974
F8	3.000000	2.861822	0.138178	0.046059
F9	3.000000	2.855916	0.144084	0.048028
F10	3.000000	2.839912	0.160088	0.053363
F11	3.000000	2.852908	0.147092	0.049031
F12	3.000000	2.878524	0.121476	0.040492
F13	3.000000	2.833628	0.166372	0.055457
F14	3.000000	2.860372	0.139628	0.046543

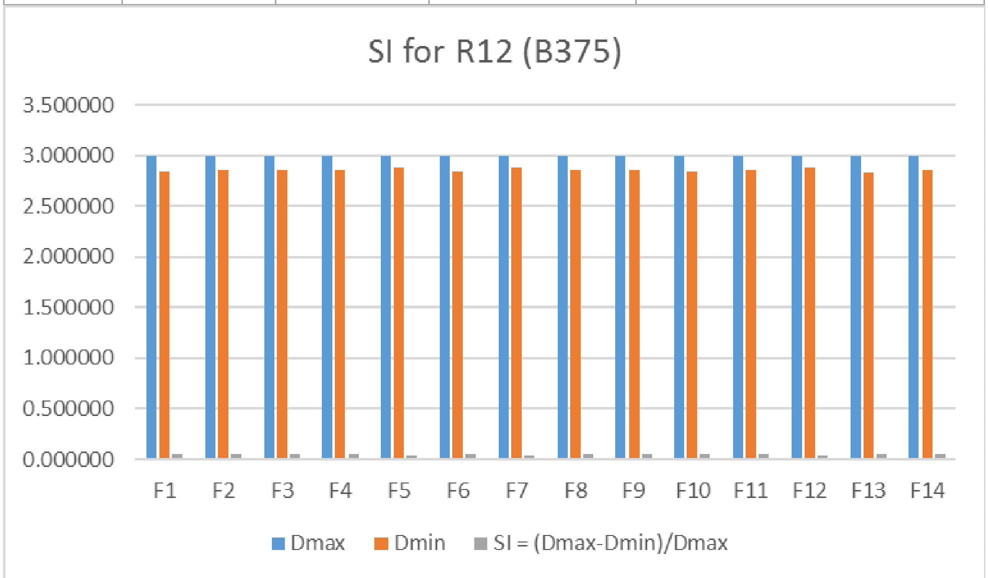

Figure 7.24a: Sensitivity Index for R12 (B375) of PMPS Equation

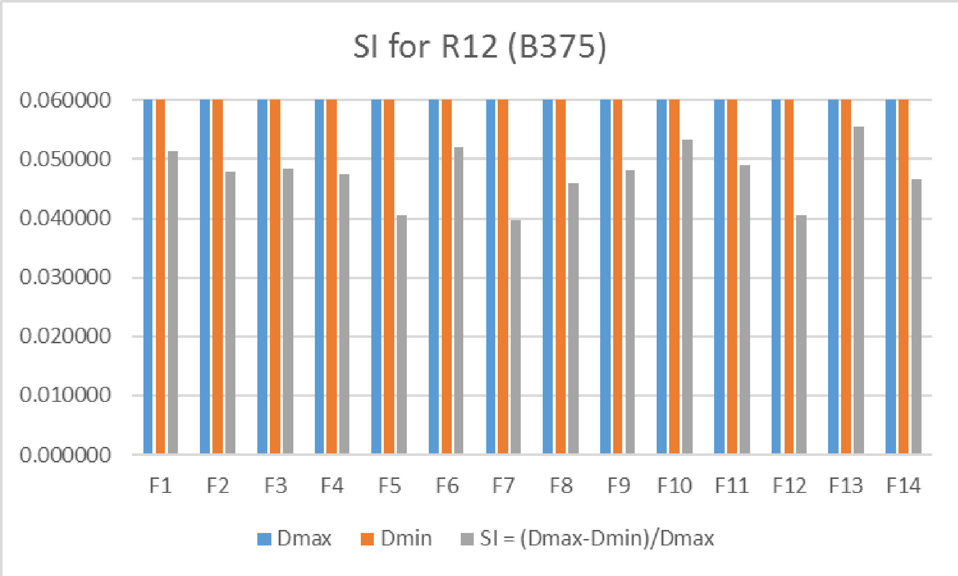

Figure 7.24b: Zoomed in Graph of Sensitivity Index for R12 (B375) of PMPS Equation

As seen from the figures given above, the highest sensitivity is observed in the thirteenth parameter which is the Available Funding factor (F13). On the other hand, the lowest values for the sensitivity index are obtained in the seventh parameter which is the Annual Average Daily Traffic (F7).

7.5 Summary of Chapter Seven

In this chapter, a prototype model has been developed in GIS. Initially, Runnymede roads are chosen as the case study in order to test the model. Subsequently, a PMPS (Pavement Maintenance Priority Score) equation has been identified. The PMPS is the structured roads prioritistion mechanism elaborated in Figure 6.2 in chapter 6.

Runnymede roads map layer has been used in GIS, which concluded 25 roads. In order to run the model, the next step was joining the PMPS equation including the scale scores of roads in terms of identified factors, which was shown in Figure 7.19, to the map layer of Runnymede roads. Graphs are shown for each PMPS term individually to enable decision makers the flexibility in making decisions.

GIS maps have been produced including the overall ranking of roads that are spatially visualised in colours in accordance with the rank of each road. As outcome, ranking of the priority scores for pavement maintenance is obtained for the case study. The results showed that R12 (B375) had the highest priority, hence it is the first road to be maintained, whilst R2 (A308) and R19 (C125) had the lowest priority, hence they are last to be maintained, which can be clearly visualised from Figure 7.23. Additionally, a sensitivity analysis for each parameter has been carried out so that decision makers are aware of the impact of each parameter on the output of the model results.

The following chapter eight comprises four interviews that have been conducted for validation purposes of the proposed model. The views of the specialists are presented in a SWOT style analysis approach.

Chapter Eight

Validation of the Model

8.1 Introduction

This chapter presents the evaluations of specialists from different local road authorities on the proposed GIS-based pavement maintenance management model in order to validate the model. Four interviews have been conducted with specialists in pavement maintenance who were previously interviewed for data collection purposes.

Throughout the interviews, the underlying mechanism is thoroughly explained, and a presentation on the proposed model is demonstrated. The specialists are then requested to evaluate the model by using a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis.

8.2 Specialists' Evaluations of the Proposed Model

The views of specialists from different local road authorities regarding the proposed model are presented in SWOT style. The following illustrate the outcome of the interviews conducted with the specialists to evaluate the model.

8.2.1 Evaluation of Specialist 1

The first specialist has 24 years of experience in GIS development and data management as a GIS and data manager at a local authority, and 8 years of experience in road management as a consultant in the private sector.

Strengths:

- Developing such a model is a good idea but will be limited by too many factors and difficulty in getting some of the data.
- Limiting its use to classes of road (A, B and C) can be effective.
- The guidance for how to assess each factor is good.

Weaknesses:

- RCI is a good consistent way of evaluating the underlying condition of the road network, however, the use of RCI is limited in unclassified roads, only 10% of roads are surveyed therefore this information must be supplemented by a visual survey, which is very expensive and labour intensive.

- The model does not consider Strategic or Community Benefits.
- Difficult to assess the available funding

Opportunities:

- The downside of using one single risk factor is that it has to be assessed by a person so there is some subjectivity.

Threats:

- Some of the factors used are not readily available for all roads, e.g. Annual average daily traffic and possible conflict with other roadworks. This may impede the use of the model.

8.2.2 Evaluation of Specialist 2

The second specialist has 15 years of experience in highways and transportation as an Asset Manager at a local authority, and is a member of the UK Road Board.

Strengths:

- GIS is an appropriate tool for network analysis
- Multi-Criteria Analysis (MCA) is the correct approach
- Seeking to involve the engineering community in the development of the proposal

Weaknesses:

- Appears to be a multi-criteria analysis tool rather than a scheme builder.
- A large number of factors are used in the model.

Opportunities:

The model is promising if some improvements are made regarding solving the logarithm in the GIS tool.

Threats:

Funding is the main issue that is worrying local authorities, hence adopting the model could be constrained due to limited budget.

8.2.3 Evaluation of Specialist 3

The third specialist has 18 years of experience in strategy development for highway assets including asset management policy and prioritisation as an Asset Planning Manager at a local authority, and is a member of the Road Condition Management Group.

Strengths:

- Brings together the primary prioritisation concerns for capital network investment planning and tries to simplify outcomes.
- Uses the opinions of industry practitioners as a basis for weighing each factor.
- I like the simple GIS banding of results by a range of colours.

Weaknesses:

- The definitions and how the scores are proposed for each band are a crucial part of the value of obtaining final outcomes from the model.
- As the model is based on planning maintenance at a network level, a large number of factors is used.
- Limited budgets for local authorities would make it difficult to afford using the model.

Opportunities:

- A simple network level tool that it appears LHA's could put their whole classified road network into fairly quickly. If scores for 1, 2, 3 factors were able to be fully described and then consistently interpreted by each individual LHA, then it can be a useful national comparison/ benchmarking tool.

Threats:

- Local road authorities may rather continue with weightings based on local knowledge, and have systems for detailed prioritisation of works rather than a more global tool.

8.2.4 Evaluation of Specialist 4

The fourth specialist has 14 years of experience in highways network management as a Principal Engineer at a local authority, and is a specialist in pavement assessment and maintenance.

Strengths:

- Sound rationale but as with many maintenance issues, whilst it is known how to prioritise schemes where funding is available, the reality is more use of preventative treatments should be identified sooner.

Weaknesses:

- Available funding permitting; worst first schemes on higher ranked roads are priorities. In fact, some amber RCI roads will still be capable of receiving preventative treatments.

Opportunities:

- Engineers might be able to see beyond worst first prioritisations and to identify where more cost effective timely preventative treatments can still be used.
- Asset Management techniques are understood by most maintenance practitioners but are not financially affordable to authorities.

Threats:

- Continued inadequate funding provisions will eventually mean that authorities will be obliged to spend more on ‘worst first’ scenarios at the expense of preventative treatments.

8.3 Conclusion of the Outcomes

STRENGTHS	*WEAKNESSES*
• Rational, simple to use and can be effective for A, B and C roads. • GIS is an appropriate tool for network analysis. • Uses opinions of the engineering community and practitioners as a basis for weighing each factor.	• Strategic or community benefits are not considered. • Might not be affordable due to limited budgets. • A large number of factors are used in the model.
OPPORTUNITIES	*THREATS*
• Improvements of the model to make scores consistently interpreted by each individual local road authority would enable the model to be a useful national comparison or benchmarking tool.	• Risk of inadequate funding may limit the practicability of the model. • Lack of some of the factors' data may impede the use of the model.

Figure 8.1: Overall SWOT Outcomes of Specialists' Views

Specialists agreed that the model is promising and would add value for the pavement maintenance field when it has improved. Feedback obtained throughout interviews confirmed the improvement possibilities to the model. The approaches used to develop the model are appreciated and participants ascertained the correct procedures followed in developing the model.

Additionally, evaluations of specialists justify the need for such a system in the management of pavement maintenance. Furthermore, the highlighted views regarding weaknesses, opportunities and threats are linked to the scope and limitations of the research, however, they would be taken into account as recommendations for future research. The opinions of the specialists regarding the number of factors due to lack of data and planned maintenance for the road network are appreciated, as applying amendments and redefining weights of factors accordingly is acceptable, on condition that steps and procedures used in developing the model have been followed.

In brief, specialists agreed that the model is rational and GIS is an appropriate tool for network analysis, and agreed that with improvements, the model would be a useful benchmarking tool.

8.4 Summary of Chapter Eight

This chapter presented the outcomes of the interviews conducted with specialists in pavement maintenance to obtain their views on the proposed model. A SWOT analysis approach is used to present the specialists' evaluations. The conclusion of the evaluations is that with consideration of improvements due to limitations, the model has been approved by specialists as a pavement maintenance prioritisation system.

The following chapter nine presents the overall conclusion of the thesis and recommendations for future research.

Chapter Nine

CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

In this chapter of the thesis, the research aim is first restated and reference is made to the research objectives in section 9.2 and then deal with the achievement of each of the six research objectives through the implementation of the research components relevant to each objective.

In Section 9.3, attention is drawn to the limitations of this research by considering the research activities in turn. Section 9.4 deals with the original contribution to knowledge made by this research.

Finally, the thesis is concluded in Section 9.5 presents a discussion of the recommendations put forward for future research in this field.

9.2 Aim and Objectives of this Research

In this section, the research aim is restated below, and reference is made to the six research objectives that are dealt with individually in the sections that follow, in order to verify their realization and state the conclusions drawn from the associated research activities.

The stated aim of this research was to *develop a GIS-based decision support model to support the decision-making process in pavement maintenance management of the existing roads under the control of Local Authorities in the UK.*

In order to achieve the above aim, the research has followed and achieved six research objectives, which are listed in sections 9.3 to 9.8 below.

9.2.1 Achievement of Objective One

Objective One was "To investigate the current pavement maintenance management practice, its principles and related challenges".

In considering the existing pavement maintenance management practices as verified through the review of the literature, it has been established that within the various local road authorities in the UK, until recently there have been different strategies and principles applied in carrying out pavement maintenance management duties. However, most local road authorities consider the condition of pavement as the only factor when planning treatments due to inadequate funding, and the principle of “worst is first” has been applied in carrying out pavement maintenance.

The historical problem of inadequate funding of pavement maintenance and management functions was highlighted within local authorities, where the inadequate funding has resulted in the build-up of a considerable backlog of maintenance work. Because paved roads are crucial parts of the transportation networks and because of the costly and highly disruptive consequences of their poor condition, pavement inspection is a vital part of the overall maintenance and management of pavement. Trained and competent pavement inspectors must undertake pavement condition inspection.

In investigating pavement maintenance, the research considered the process through which pavement deterioration takes place, as a result of one or more factors such as weathering resulting in natural deterioration; design and detailing faults, and faulty materials. However, the most important factor in the continual deterioration of pavement has in fact been the past neglect, which is the lack of adequate maintenance, due to inadequate funding. What is therefore important in pavement maintenance is deciding on the timing and level of intervention, which are in effect the main outcomes of pavement maintenance prioritisation.

The importance of effective pavement maintenance was therefore confirmed based on the premise that, unless remedial actions are implemented quickly, pavement may be considered at risk of failure during its functional life due mainly to one or more of the deterioration factors highlighted above.

The existing pavement management practices within the UK local road authorities were investigated in the literature review to assess any evident inadequacies and gaps in the current practices. Based on the literature review, it is clear that despite the major developments in pavement maintenance techniques in the last few years, and the existence of pavement management and maintenance systems in the UK, local road authorities need to adopt a joint effort strategy to develop these systems.

9.2.2 Achievement of Objective Two

Objective Two was "To establish the most significant factors that influence decision making in Pavement Maintenance Management".

This objective was achieved initially through the literature review and then refined and validated through the questionnaire survey which was undertaken with the aim of establishing a general consensus amongst local authorities' practising road engineers and managers as to the most significant factors affecting pavement maintenance management prioritisation decisions.

Establishing the most significant factors effecting pavement maintenance prioritisation was therefore based on a consensus of 67 practising Local Road Authority road engineers and managers, as specialists in their field, representing a 34% response rate to the questionnaire survey carried out for this purpose.

A total of 14 factors were initially identified by the researcher, based on the literature review but adjusted slightly based on the pilot survey. These factors were included in the questionnaire survey as the most important factors affecting the prioritisation decisions in pavement maintenance. After obtaining the rated factors from participants, interviews with specialists in pavement maintenance from different local authorities were conducted in order to justify the rating of the factors.

9.2.3 Achievement of Objective Three

Objective Three was "To explore the best practices from real life and research on the methods of pavement maintenance management with GIS".

In carrying out the review of the available literature on the use of GIS in pavement maintenance management, it is evident that there is a solid agreement that GIS has a major advantage in being able to collect, archive, and analyse pavement data. Another acknowledged advantage of GIS is its ability to handle spatial data and visualise it using maps.

GIS is therefore suitable for tackling problems with spatial data and predicting, which are at the centre of pavement maintenance prioritisation and decision-making.

9.2.4 Achievement of Objective Four

Objective Four was "To specify a conceptual model that employs a Multi-Criteria Decision Making (MCDM) approach for effective pavement maintenance management using GIS as a decision support tool".

The specifications of the proposed model supporting decision makers were described and discussed. First, a description of the functionality of the model was provided in order to justify its proposed application, followed by an outline of the data requirements of the model and its structure. The components of the model were presented, and then the proposed model was illustrated from a conceptual point of view.

Data processing and analysis was based on AHP where MCDM methods were convenient for solving complex problems such as the prioritisation of maintenance works for the overall road network. Relative weights of factors were estimated and rankings of alternative roads were calculated based on the AHP algorithm, which were explained in chapter 6.

The required data for the model were identified. Firstly, a digital base map in GIS was required that provides a detailed view of individual roads. Secondly, the identified 14 factors that affect pavement maintenance were required in order to develop the model.

The components of the proposed model for pavement maintenance management were presented in four phases as follows:

- Identifying factors affecting pavement maintenance priority
- Processing mechanism and appropriate procedures to deal with the affecting factors (in this case, AHP algorithm).
- Estimation and calculation of the model's parameters
- Application of the model for pavement maintenance priority

A conceptual model was specified in which the main input and imported database into GIS as well as the main output were shown in a conceptual framework. Therefore, the proposed model was illustrated in chapter 6, Figure 6.5 from a conceptual point of view.

9.2.5 Achievement of Objective Five

Objective Five was "To implement the conceptual model proposed in the previous objective in GIS via use of ArcGIS software, to demonstrate the conceptual model as a decision support tool in order to enhance decision making in pavement maintenance management and to test the proposed model based on GIS via a case study of Runnymede roads within the Surrey County Council".

A prototype model has been developed for a case study of Runnymede roads within the Surrey county council, in which a data layer of geographical locations of Runnymede roads has been assigned to the digital map (base map). A formula for obtaining the Pavement Maintenance Priority Score (PMPS) has been developed, which is the base for ranking the alternatives.

A scale of 1 to 3 has been used for the factors according to their description, and then the scores of the 14 factors for each factor 1 or 2 or 3 have been assigned to each defected road as shown in table 7.16, chapter 7. As no real data were available due to difficulties accessing that data, assumptions were made in order to assign a score for each factor.

PMPS was calculated via Excel software using the logarithm below:

$$\begin{aligned} PMPS = [&(F_1 * W_1) + (F_2 * W_2) + (F_3 * W_3) + (F_4 * W_4) + (F_5 * W_5) + \\ &(F_6 * W_6) + (F_7 * W_7) + (F_8 * W_8) + (F_9 * W_9) + (F_{10} * W_{10}) + \\ &(F_{11} * W_{11}) + (F_{12} * W_{12}) + (F_{13} * W_{13}) + (F_{14} * W_{14})] \end{aligned}$$

Where, F is the Score of Factor and W is the Weight of Factor.

The spreadsheet then has been integrated into ArcGIS software with GIS base map layer of Runnymede roads. The results have been visualised in the GIS map including the ranking of the 25 defected roads.

9.2.6 Achievement of Objective Six

Objective Six was "To validate the implemented model via validation interviews with industry practitioners from different local authorities".

Validation interviews with specialists in pavement maintenance have been conducted in order to validate the model. The assessment mechanism of the model has been explained and the outputs have been demonstrated. The specialists have evaluated the model by using SWOT analysis. The obtained feedback indicated that the model is rational, simple and appropriate. Issues that were addressed included limited funding and considering strategic or community benefits, and these were linked to the scope and limitations of this study. On the whole, the GIS-based pavement maintenance management model has been validated and can be applicable in the future.

9.3 Research Limitations

As with any research, there are limitations within issues affecting the research methodology, the analytical techniques and processes adopted and the interpretation of the results particularly when attempting to make generalisations. The most significant limitations considered to affect this research are discussed here.

For the questionnaire survey, the target participant population is comprised of practising pavement engineers and managers in local road authorities representing all regions of the UK. A reasonable response rate of 34% was achieved, considering the widely acknowledged low response rate within questionnaire research.

However, as with any survey-based research generally, there are limitations in the interpretation of the results, since although a pilot survey was carried out prior to the implementation of the main survey, different interpretations of the questions by different respondents may have an effect on the answers given.

In addition, while the research is specifically targeted at local road authorities within the UK as defined by the research design, a limitation does exist however when considering the wider road agencies, in that any generalisation made about the results of the survey could only be made within the local road authority sphere.

Furthermore, factors affecting pavement maintenance prioritisation used in the research are identified from literature and discussions with specialists in pavement maintenance. However, as different individual local road authorities may add or ignore some factors to suit their need due to lack of data regarding these factors, there are limitations in the accessibility of data, hence assumptions have been made for defining and scaling the factors.

Important features of the GIS application are the convenience for spatial components and visualisation of data on maps. However, a limitation of this tool, as relevant to this research, is being as part of combined systems with an AHP approach to calculate the MCDM algorithm and not as a stand-alone system. In this study, the PMPS equation has been calculated in Excel software and then imported to ArcGIS software.

9.4 Original Contributions of this Research

There are two main practical components to this research, one input component and one output. The input component is the questionnaire survey and the output component of the research is the GIS-based model, which is developed as a decision support tool. The two research components have, to varying extents, contributed to knowledge.

Regarding the questionnaire survey, according to the Author's knowledge, this is the first research work to enquire into the most significant factors affecting pavement maintenance prioritisation decisions since the publication of the "Well-maintained Highways: Code of Practice for Highway Maintenance Management" in 2005, which started to be gradually applied in local road authorities from 2006 onwards. The research is also the first to concentrate on local road authorities only as target participants and to exclude all other road agencies, because the research is focused on improving pavement maintenance management practices in local road authorities. The outcome is considered original, and the collected data and the data analysis contribute to knowledge.

Many research works have been conducted into the use of GIS-based models in classification problems including the application into pavement maintenance prioritisation and optimisation. However, in this research the development of the model was carried out specifically using data obtained from specialists in pavement maintenance from local road authorities. In addition, testing and validation of the model were carried out specifically using a local road authority as a case study and specialists from local road authorities respectively. Furthermore, the 14 factors obtained from the survey were scored by the Author, using what the Author considers to be a unique methodology for assigning the scores that correspond to priority, which represents a contribution of this research.

9.5 Recommendations for Further Research

Considering the questionnaire survey, future research could widen the survey coverage to all different road agencies including the Highway Agency, while maintaining the same objectives and research theme. This would be of great benefit to gain wider experience from different approaches to pavement maintenance management.

Priority scores assigned to each factor as a scale according to the description and classification of the factors is a unique methodology. However, improvement of the classification to make scores consistently interpreted by each individual local road authority could be considered for future research.

Regarding the GIS-based model as a decision support tool, this research concentrated on prioritisation based on a subsystem to calculate the priority score equation, where it is then imported into GIS. However, an important aspect of future research should consider using GIS as a standalone decision support tool.

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APPENDIX A

Questionnaire Survey

<u>Pavement Maintenance Prioritisation Survey Questionnaire</u>

Dear Sir/Madam,

Study into GIS-based Pavement Maintenance Management Model for Local Roads in the UK

This questionnaire is part of a study conducted by The University of Salford as part of a PhD research programme into decision making in pavement maintenance management and the prioritisation of pavement maintenance schemes.

The questionnaire is aimed at local authorities' road managers and engineers engaged in the maintenance of pavement; or pavement maintenance agents working on behalf of local authorities to maintain pavement in their area.

The research objectives include verifying the most significant factors used in prioritising pavement maintenance schemes; assessing current pavement maintenance prioritisation methods; and developing a GIS-based model to enhance the prioritisation decisions of pavement maintenance schemes.

In order to make our research more beneficial and applicable, we would value your opinion about the factors governing the decision making process for prioritising pavement maintenance activities and their relative importance.

We would appreciate your help in this research by completing the questionnaire below and return it to Emad Alfar by e-mail or alternatively by post to the address below.

If you are unable to complete the questionnaire due to a lack of knowledge of the issues involved, we would be grateful if you would pass it to another person who would be able to answer the questions.

We thank you for your assistance.

Emad Alfar (PhD student)

School of Built Environment

University of Salford

E-mail address: emadelfar@hotmail.com

e.alfar@edu.salford.ac.uk

1. About your organisation

Please put "x" in the relevant box.

1.1 What type of organisation do you represent?

Road		Maintaining Agent		Other	

If 'Maintaining Agent' or 'Other' please give details

If 'Road Authority', please specify

County		Metropolitan		Other	

If 'other', please specify

1.2 Length of roads your organisation is responsible for?

1.3 What is the average budget per annum of pavement maintenance schemes in your organisation?

£

2. Pavement Maintenance Priority Factors

Please put 'x' in the appropriate box to indicate the degree of importance of the following factors in the prioritisation decisions for road maintenance schemes. Please mark your answers according to the following scale:

1 = Not important

2 = Less important

3 = Important

4 = Very important

5 = Extremely important

No.	Factors	Importance				
		1	2	3	4	5
1	Remaining Service Life					
2	Road Condition Indicator (RCI)					
3	Type of Deterioration					
4	Observed Deterioration Rate					
5	Traffic Diversion					
6	Importance/Classification of Road					
7	Annual Average Daily Traffic (AADT)					
8	Possible Conflict or Overlap with Other Road Works					
9	Risk of Failure					

No.	Factors	Importance				
		1	2	3	4	5
10	Safety Concern					
11	Accident Rate (related to surface condition)					
12	Scheme Cost					
13	Available Funding					
14	Whole Life-cycle Cost					

Please list any other factors, which are not included in the above table and indicate their degree of influence accordingly:

No.	Factors	Importance				
		1	2	3	4	5
1						
2						
3						
4						

Please add below any comments or views regarding this questionnaire

If you would like to be sent the main findings of this survey, please enter your name and e-mail or business address below:

Name:

E-mail / Business Address:

Thank you

APPENDIX B

Pilot Survey Feedback Questionnaire

Dear Sir/Madam,

<u>Feedback on the Study into Pavement Maintenance Prioritisation</u>

I should be grateful if you would complete and return this feedback questionnaire, which is aimed at testing the adequacy and effectiveness of the main research questionnaire.

Please answer the attached questions relating to the main survey questionnaire and return to me at the address given below or by e-mail.

Thank you for your assistance.

Emad Alfar (PhD student)

Emad Alfar

School of Built Environment

University of Salford

E-mail address: emadelfar@hotmail.com

e.alfar@edu.salford.ac.uk

1. How effective is the technique used to obtain the data?

	Effective		Fairly Effective		Not Effective

Comments:

2. How effective is the invitation to respondents?

	Effective		Fairly Effective		Not Effective

Comments:

3. Are the instructions clear?

	Clear		Fairly Clear		Some Not Clear

Comments:

4. How clear is the wording of questions?

	Clear		Fairly Clear		Some Not Clear

Which questions are not clear?

5. Length of time it took to complete the questionnaire?

Minutes

6. Do you consider this time to be reasonable?

Yes No

Comments :

7. Do you consider the questions to adequately cover the subject topic?

☐ Yes ☐ No

Please comment on any possible omission of any topic:

8. Please provide any additional comments or feedback on the questionnaire layout, objectivity of the questions and listed factors:

Thank you

APPENDIX C

Local Road Authorities Consulted by Questionnaire Survey and those that Responded

No.	Local Authorities Consulted	Type	Response Outcome
1	Buckinghamshire	CC	
2	Cambridgeshire	CC	
3	Cornwall	CC	
4	Cumbria	CC	Responded (1)
5	Derbyshire	CC	
6	Devon	CC	Responded (2)
7	Dorset	CC	Responded (3)
8	East Sussex	CC	
9	Essex	CC	Responded (4)
10	Gloucestershire	CC	Responded (5)
11	Hampshire	CC	Responded (6)
12	Hertfordshire	CC	
13	Kent	CC	
14	Lancashire	CC	Responded (7)
15	Leicestershire	CC	Responded (8)
16	Lincolnshire	CC	
17	Norfolk	CC	Responded (9)
18	North Yorkshire	CC	
19	Northamptonshire	CC	Responded (10)
20	Nottinghamshire	CC	
21	Oxfordshire	CC	
22	Rutland	CC	
23	Shropshire	CC	Responded (11)

No.	Local Authorities Consulted	Type	Response Outcome
24	Somerset	CC	Responded (12)
25	Staffordshire	CC	
26	Suffolk	CC	Responded (13)
27	Surrey	CC	Responded (14)
28	Warwickshire	CC	
29	West Sussex	CC	
30	Worcestershire	CC	
31	Barnsley	MB	
32	Birmingham City	MB	Responded (15)
33	Bolton	MB	
34	Bury	MB	
35	Calderdale	MB	Responded (16)
36	City of Bradford	MB	
37	Coventry City	MB	
38	Doncaster	MB	
39	Gateshead	MB	
40	Kirklees	MB	
41	Knowsley	MB	
42	Leeds City	MB	Responded (17)
43	Liverpool City	MB	Responded (18)
44	Manchester City	MB	Responded (19)
45	Newcastle City	MB	
46	North Tyneside	MB	
47	Oldham	MB	
48	Rochdale	MB	
49	Rotherham	MB	
50	Salford City	MB	Responded (20)
51	Sandwell	MB	

No.	Local Authorities Consulted	Type	Response Outcome
52	Sefton	MB	
53	Sheffield	MB	
54	Solihull	MB	
55	South Tyneside	MB	
56	ST Helens	MB	
57	Stockport	MB	
58	Sunderland City	MB	Responded (21)
59	Tameside	MB	Responded (22)
60	Trafford	MB	
61	Wakefield City	MB	Responded (23)
62	Walsall	MB	Responded (24)
63	Wigan	MB	
64	Wirral	MB	
65	Wolverhampton	MB	
66	Barking and Dagenham	LB	Responded (25)
67	Barnet	LB	Responded (26)
68	Bexley	LB	
69	Brent	LB	
70	Bromley	LB	
71	Camden	LB	Responded (27)
72	Croydon	LB	
73	Ealing	LB	
74	Enfield	LB	
75	Greenwich	LB	
76	Hackney	LB	
77	Hammersmith and Fulham	LB	Responded (28)
78	Haringey	LB	
79	Harrow	LB	Responded (29)

No.	Local Authorities Consulted	Type	Response Outcome
80	Havering	LB	Responded (30)
81	Hillingdon	LB	
82	Hounslow	LB	
83	Islington	LB	Responded (31)
84	Lambeth	LB	
85	Lewisham	LB	
86	Merton	LB	Responded (32)
87	Newham	LB	Responded (33)
88	Redbridge	LB	
89	Richmond Upon Thames	LB	Responded (34)
90	Southwark	LB	
91	Sutton	LB	Responded (35)
92	Tower Hamlets	LB	
93	Waltham Forest	LB	
94	Wandsworth	LB	
95	Kensington and Chelsea	LB	
96	Kingston Upon Thames	LB	
97	Westminster City	LB	
98	Bath and North East Somerset	UA	Responded (36)
99	Bedford	UA	
100	Blackburn and Darwen	UA	
101	Bournemouth	UA	
102	Bracknell Forest	UA	
103	Brighton and Hove	UA	
104	Bristol City	UA	
105	Central Bedfordshire	UA	Responded (37)
106	Cheshire East	UA	
107	Cheshire West and Chester	UA	Responded (38)

No.	Local Authorities Consulted	Type	Response Outcome
108	City of York	UA	Responded (39)
109	Derby City	UA	
110	Durham	UA	
111	East Riding of Yorkshire	UA	Responded (40)
112	Halton	UA	Responded (41)
113	Hartlepool	UA	
114	Herefordshire	UA	
115	Hull City	UA	Responded (42)
116	Leicester City	UA	
117	Luton	UA	Responded (43)
118	Middlesbrough	UA	Responded (44)
119	Milton Keynes	UA	
120	North East Lincolnshire	UA	
121	North Lincolnshire	UA	
122	North Somerset	UA	
123	Northumberland	UA	Responded (45)
124	Nottingham City	UA	
125	Peterborough City	UA	
126	Plymouth City	UA	
127	Poole	UA	
128	Portsmouth	UA	
129	Reading	UA	
130	Redcar and Cleveland	UA	Responded (46)
131	Windsor and maidenhead	UA	
132	South Gloucestershire	UA	Responded (47)
133	Southampton City	UA	
134	Southend on Sea	UA	Responded (48)
135	Stockton on Tees	UA	

No.	Local Authorities Consulted	Type	Response Outcome
136	Stoke on Trent City	UA	
137	Swindon	UA	Responded (49)
138	Telford and Wrekin	UA	
139	Torbay	UA	Responded (50)
140	Warrington	UA	Responded (51)
141	West Berkshire	UA	
142	Wiltshire	UA	Responded (52)
143	Wokingham	UA	Responded (53)
144	Aberdeen City	UA	Responded (54)
145	Aberdeenshire	UA	
146	Argyll and Bute	UA	
147	City of Edinburgh	UA	Responded (55)
148	Clackmannanshire	UA	Responded (56)
149	Dundee City	UA	
150	East Ayrshire	UA	Responded (57)
151	East Dunbartonshire	UA	
152	East Lothian	UA	
153	East Renfrewshire	UA	
154	Falkirk	UA	
155	Fife	UA	
156	Glasgow City	UA	Responded (58)
157	Highland	UA	
158	Midlothian	UA	
159	Moray	UA	
160	North Ayrshire	UA	
161	North Lanarkshire	UA	
162	Perth and Kinross	UA	
163	Renfrewshire	UA	

No.	Local Authorities Consulted	Type	Response Outcome
164	South Ayrshire	UA	
165	South Lanarkshire	UA	
166	Stirling	UA	
167	West Dunbartonshire	UA	
168	Western Isles	UA	Responded (59)
169	Blaenau Gwent	UA	
170	Bridgend	UA	
171	Caerphilly	UA	
172	Carmarthenshire	UA	
173	Ceredigion	UA	Responded (60)
174	City and County of Cardiff	UA	Responded (61)
175	City and County of Swansea	UA	
176	Conwy	UA	
177	Denbighshire	UA	
178	Flintshire	UA	
179	Gwynedd	UA	
180	Isle of Anglesey	UA	
181	Merthyr Tydfil	UA	
182	Monmouthshire	UA	
183	Neath Port Talbot	UA	
184	Newport City	UA	
185	Pembrokeshire	UA	Responded (62)
186	Powys	UA	Responded (63)
187	Rhondda Cynon Taff	UA	Responded (64)
188	The Vale of Glamorgan	UA	
189	Torfaen	UA	
190	Wrexham	UA	Responded (65)
191	Eastern Division – DRDNI Department for Regional	RS	

No.	Local Authorities Consulted	Type	Response Outcome
	Development in Northern Ireland		
192	Northern Division – DRDNI Department for Regional Development in Northern Ireland	RS	
193	Southern Division – DRDNI Department for Regional Development in Northern Ireland	RS	
194	Western Division – DRDNI Department for Regional Development in Northern Ireland	RS	Responded (66)
195	AMEY	RA	Responded (67)

Key to Acronyms Used: CC = County Council MB = Metropolitan Borough

LB = London Borough UA = Unitary Authority

RS = Road Service RA = Road Agency

APPENDIX D

Justifying the Rating of the Factors Affecting Pavement Maintenance Prioritisation

1. Background and General Information

Name:

Address:

Date of Interview:

Position:

Experiences in pavement maintenance sector:

2. Please state the reasons for rating the factors affecting Pavement Maintenance prioritisation.

1 = Not Important
2 = Less Important
3 = Important
4 = Very Important
5 = Extremely Important

Factor	**Rating**	**Reason**
Remaining Service Life		
Road Condition Indicator RCI		
Type of Deterioration		
Observed Deterioration Rate		
Traffic Diversion		
Importance/Classification of Road		
Annual Average Daily Traffic (AADT)		
Possible Conflict with Other Road Works		
Risk of Failure		
Safety Concern		

Accident Rates (related to condition surface)		
Scheme Cost		
Available Funding		
Whole Life-cycle Cost		

APPENDIX E

Reliability Results by Using SPSS

Case Processing Summary

		N	%
Cases	Valid	67	100.0
	Excluded[a]	0	.0
	Total	67	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.740	14

Item Statistics

	Mean	Std. Deviation	N
Remaining Service Life	4.149	1.0188	67
Road Condition Indicator (RCI)	3.866	.9028	67
Type of Deterioration	3.910	.8830	67
Observed Deterioration Rate	3.836	1.0531	67
Traffic Diversion	3.284	1.2285	67
Importance/Classification of Road	4.209	.7290	67
Annual Average Daily Traffic (AADT)	3.209	1.0081	67
Possible Conflict or Overlap with Other Road Works	3.716	1.0121	67
Risk of Failure	3.881	1.1351	67
Safety Concern	4.313	.9408	67
Accident Rate (related to surface condition)	3.955	1.1472	67
Scheme Cost	3.269	1.0672	67
Available Funding	4.478	.9105	67
Whole Life-cycle Cost	3.761	1.0884	67

Item-Total Statistics

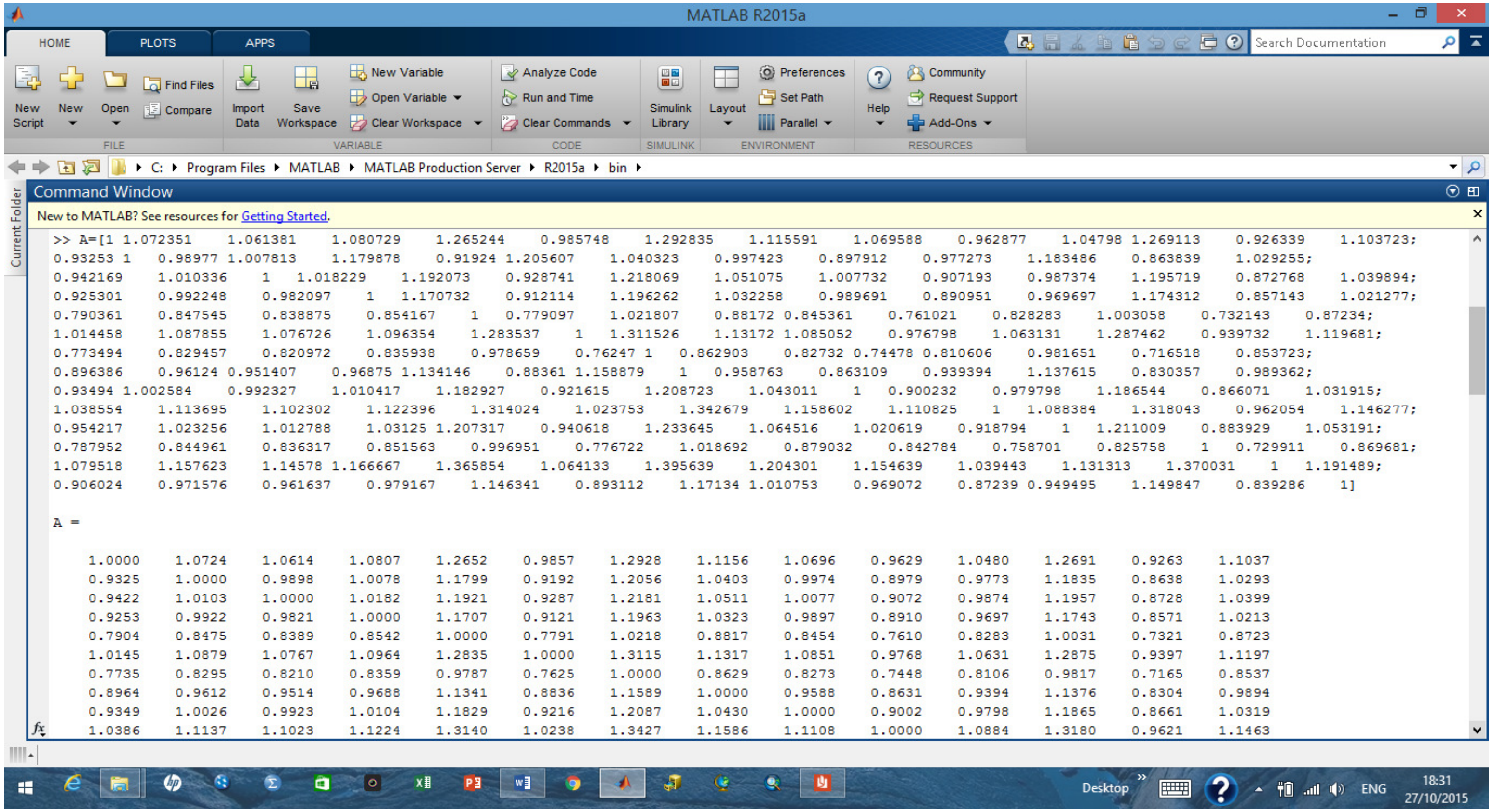
	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Remaining Service Life	49.687	42.309	.213	.740
Road Condition Indicator (RCI)	49.970	43.029	.196	.740
Type of Deterioration	49.925	39.343	.546	.706
Observed Deterioration Rate	50.000	40.788	.318	.729
Traffic Diversion	50.552	39.281	.349	.726
Importance/Classification of Road	49.627	42.177	.366	.725
Annual Average Daily Traffic (AADT)	50.627	39.874	.415	.718
Possible Conflict or Overlap with Other Road Works	50.119	41.076	.314	.729
Risk of Failure	49.955	39.468	.380	.722
Safety Concern	49.522	41.102	.347	.725
Accident Rate (related to surface condition)	49.881	38.470	.449	.713
Scheme Cost	50.567	40.340	.346	.725
Available Funding	49.358	40.991	.373	.723
Whole Life-cycle Cost	50.075	40.252	.343	.726

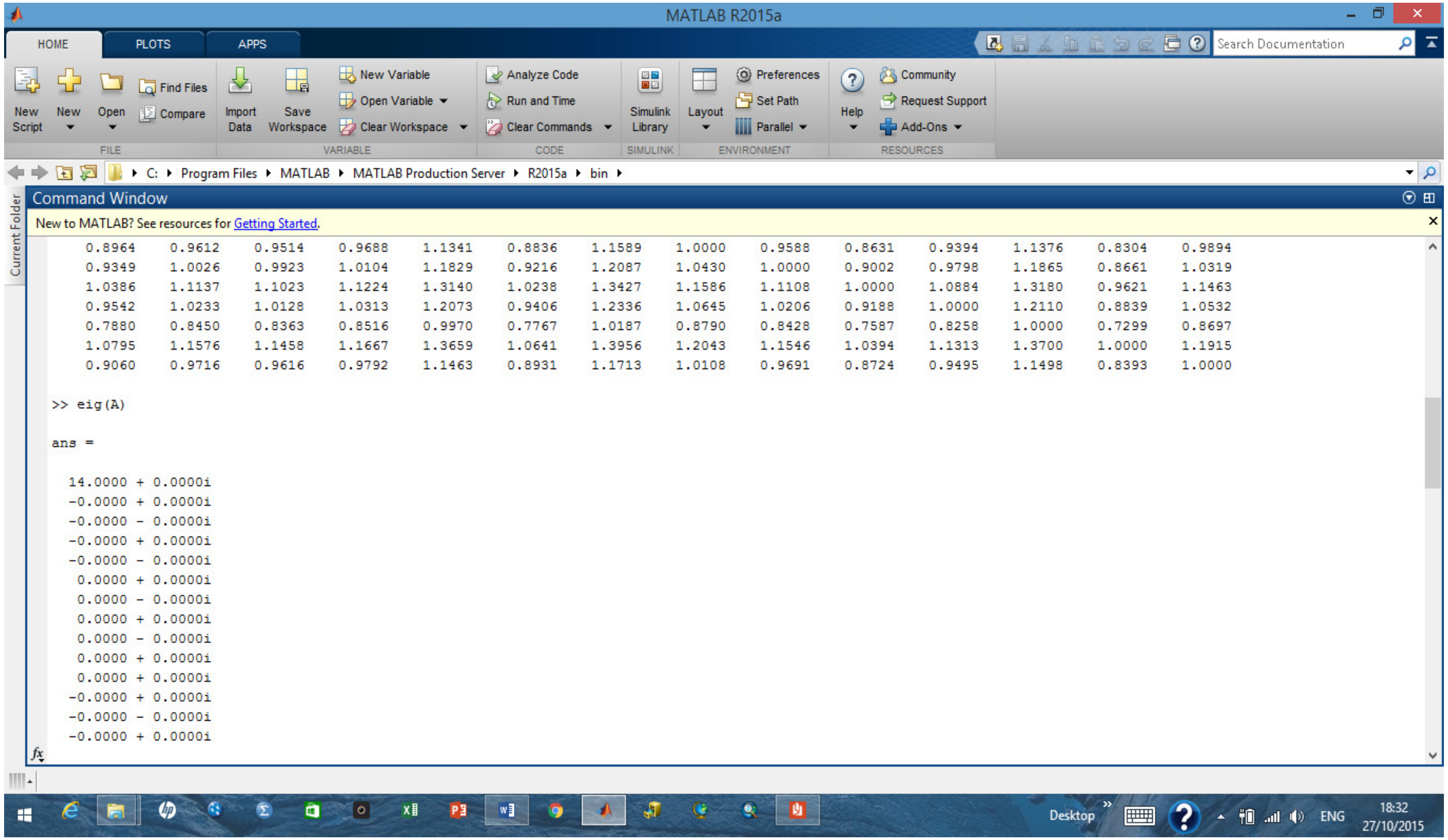
Scale Statistics

Mean	Variance	Std. Deviation	N of Items
53.836	46.170	6.7948	14

APPENDIX F

Calculation of Eigenvalues and Eigenvectors in MATLAB R2015a




MATLAB R2015a
HOME
PLOTS
APPS
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New Script
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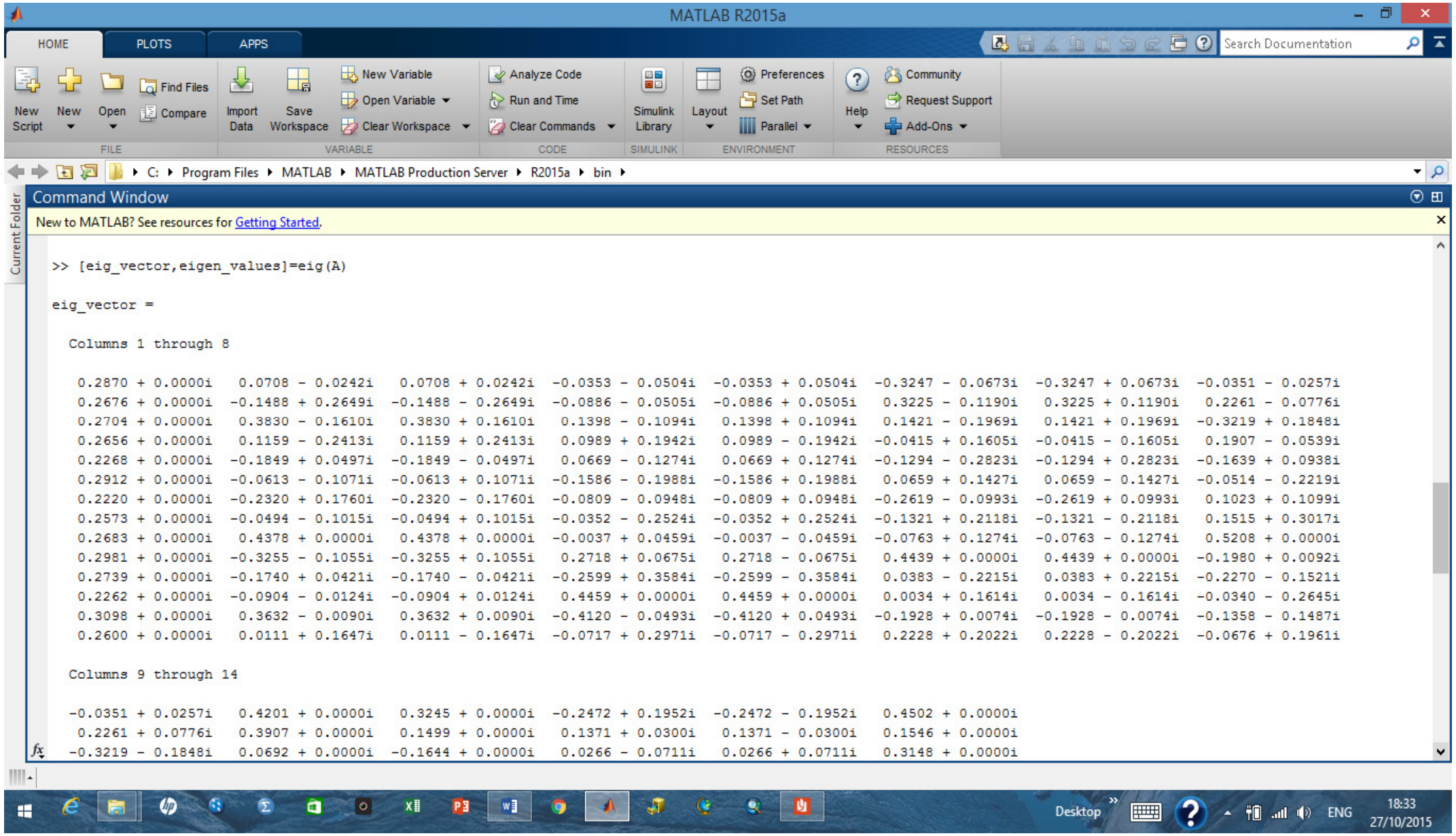
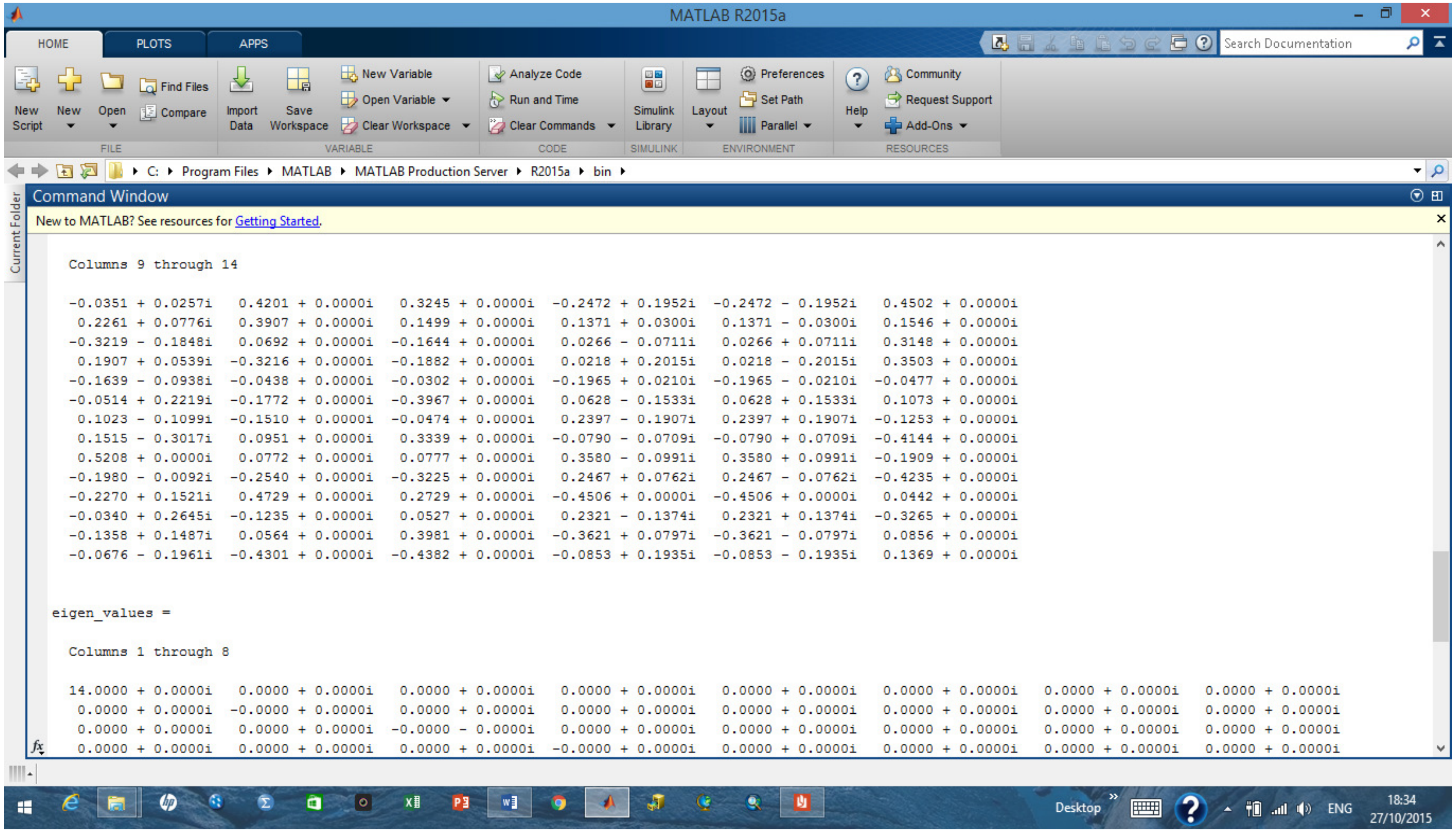
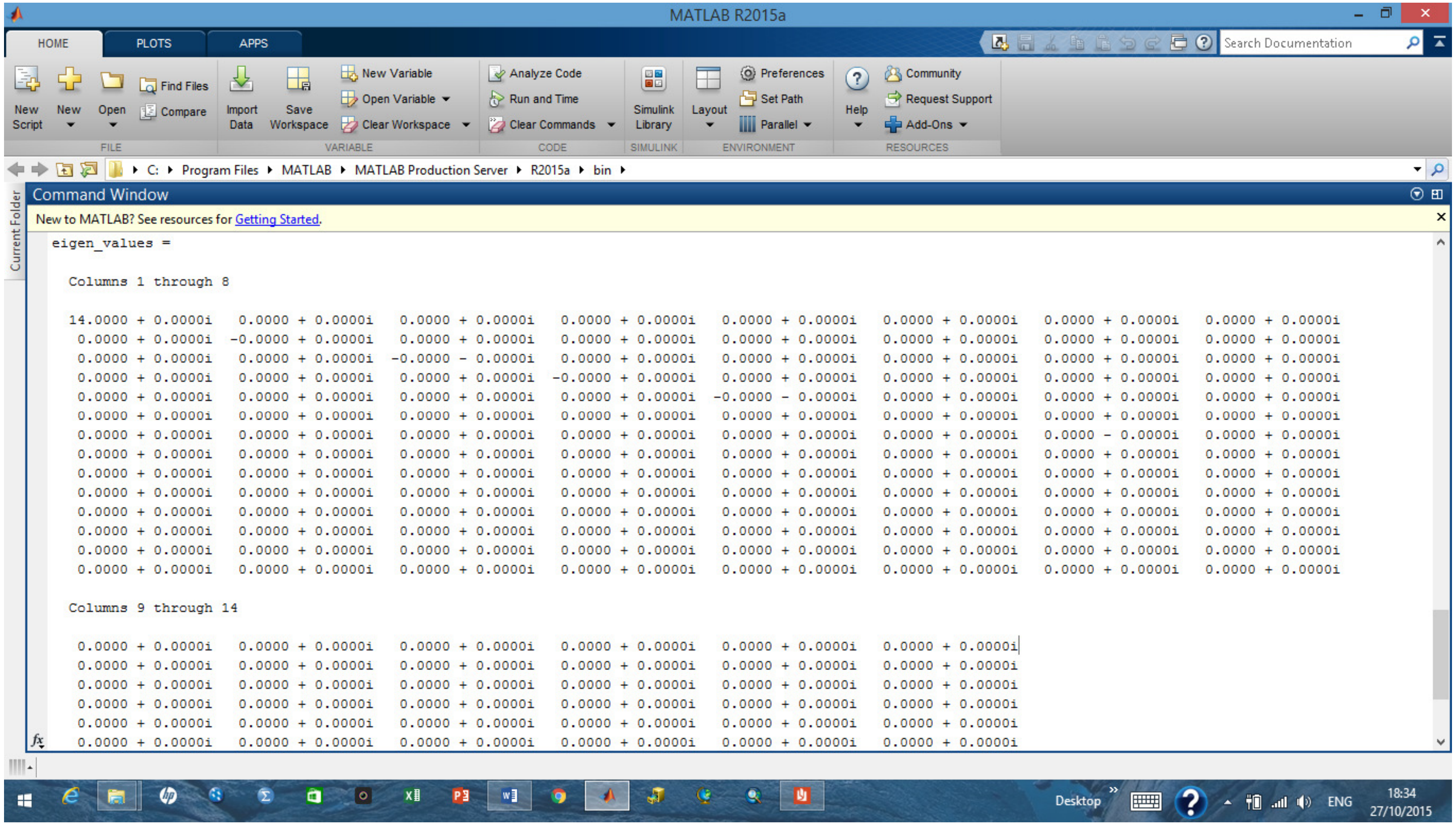
Find Files
Compare
Import Data
Save Workspace
New Variable
Open Variable
Clear Workspace
Analyze Code
Run and Time
Clear Commands
Simulink Library
Layout
Preferences
Set Path
Parallel
Help
Community
Request Support
Add-Ons
FILE
VARIABLE
CODE
SIMULINK
ENVIRONMENT
RESOURCES
C: ▸ Program Files ▸ MATLAB ▸ MATLAB Production Server ▸ R2015a ▸ bin ▸
Current Folder
Command Window
New to MATLAB? See resources for Getting Started.
0.8964 0.9612 0.9514 0.9688 1.1341 0.8836 1.1589 1.0000 0.9588 0.8631 0.9394 1.1376 0.8304 0.9894
0.9349 1.0026 0.9923 1.0104 1.1829 0.9216 1.2087 1.0430 1.0000 0.9002 0.9798 1.1865 0.8661 1.0319
1.0386 1.1137 1.1023 1.1224 1.3140 1.0238 1.3427 1.1586 1.1108 1.0000 1.0884 1.3180 0.9621 1.1463
0.9542 1.0233 1.0128 1.0313 1.2073 0.9406 1.2336 1.0645 1.0206 0.9188 1.0000 1.2110 0.8839 1.0532
0.7880 0.8450 0.8363 0.8516 0.9970 0.7767 1.0187 0.8790 0.8428 0.7587 0.8258 1.0000 0.7299 0.8697
1.0795 1.1576 1.1458 1.1667 1.3659 1.0641 1.3956 1.2043 1.1546 1.0394 1.1313 1.3700 1.0000 1.1915
0.9060 0.9716 0.9616 0.9792 1.1463 0.8931 1.1713 1.0108 0.9691 0.8724 0.9495 1.1498 0.8393 1.0000
>> eig(A)
ans =
14.0000 + 0.0000i
-0.0000 + 0.0000i
-0.0000 - 0.0000i
-0.0000 + 0.0000i
-0.0000 - 0.0000i
0.0000 + 0.0000i
0.0000 - 0.0000i
0.0000 + 0.0000i
0.0000 - 0.0000i
0.0000 + 0.0000i
0.0000 + 0.0000i
-0.0000 + 0.0000i
-0.0000 - 0.0000i
-0.0000 + 0.0000i
Desktop
ENG
18:32
27/10/2015




```
>> [eig_vector,eigen_values]=eig(A)

eig_vector =

  Columns 1 through 8

   0.2870 + 0.0000i   0.0708 - 0.0242i   0.0708 + 0.0242i  -0.0353 - 0.0504i  -0.0353 + 0.0504i  -0.3247 - 0.0673i  -0.3247 + 0.0673i  -0.0351 - 0.0257i
   0.2676 + 0.0000i  -0.1488 + 0.2649i  -0.1488 - 0.2649i  -0.0886 - 0.0505i  -0.0886 + 0.0505i   0.3225 - 0.1190i   0.3225 + 0.1190i   0.2261 - 0.0776i
   0.2704 + 0.0000i   0.3830 - 0.1610i   0.3830 + 0.1610i   0.1398 - 0.1094i   0.1398 + 0.1094i   0.1421 - 0.1969i   0.1421 + 0.1969i  -0.3219 + 0.1848i
   0.2656 + 0.0000i   0.1159 - 0.2413i   0.1159 + 0.2413i   0.0989 + 0.1942i   0.0989 - 0.1942i  -0.0415 + 0.1605i  -0.0415 - 0.1605i   0.1907 - 0.0539i
   0.2268 + 0.0000i  -0.1849 + 0.0497i  -0.1849 - 0.0497i   0.0669 - 0.1274i   0.0669 + 0.1274i  -0.1294 - 0.2823i  -0.1294 + 0.2823i  -0.1639 + 0.0938i
   0.2912 + 0.0000i  -0.0613 - 0.1071i  -0.0613 + 0.1071i  -0.1586 - 0.1988i  -0.1586 + 0.1988i   0.0659 + 0.1427i   0.0659 - 0.1427i  -0.0514 - 0.2219i
   0.2220 + 0.0000i  -0.2320 + 0.1760i  -0.2320 - 0.1760i  -0.0809 - 0.0948i  -0.0809 + 0.0948i  -0.2619 - 0.0993i  -0.2619 + 0.0993i   0.1023 + 0.1099i
   0.2573 + 0.0000i  -0.0494 - 0.1015i  -0.0494 + 0.1015i  -0.0352 - 0.2524i  -0.0352 + 0.2524i  -0.1321 + 0.2118i  -0.1321 - 0.2118i   0.1515 + 0.3017i
   0.2683 + 0.0000i   0.4378 + 0.0000i   0.4378 + 0.0000i  -0.0037 + 0.0459i  -0.0037 - 0.0459i  -0.0763 + 0.1274i  -0.0763 - 0.1274i   0.5208 + 0.0000i
   0.2981 + 0.0000i  -0.3255 - 0.1055i  -0.3255 + 0.1055i   0.2718 + 0.0675i   0.2718 - 0.0675i   0.4439 + 0.0000i   0.4439 + 0.0000i  -0.1980 + 0.0092i
   0.2739 + 0.0000i  -0.1740 + 0.0421i  -0.1740 - 0.0421i  -0.2599 + 0.3584i  -0.2599 - 0.3584i   0.0383 - 0.2215i   0.0383 + 0.2215i  -0.2270 - 0.1521i
   0.2262 + 0.0000i  -0.0904 - 0.0124i  -0.0904 + 0.0124i   0.4459 + 0.0000i   0.4459 + 0.0000i   0.0034 + 0.1614i   0.0034 - 0.1614i  -0.0340 - 0.2645i
   0.3098 + 0.0000i   0.3632 - 0.0090i   0.3632 + 0.0090i  -0.4120 - 0.0493i  -0.4120 + 0.0493i  -0.1928 + 0.0074i  -0.1928 - 0.0074i  -0.1358 - 0.1487i
   0.2600 + 0.0000i   0.0111 + 0.1647i   0.0111 - 0.1647i  -0.0717 + 0.2971i  -0.0717 - 0.2971i   0.2228 + 0.2022i   0.2228 - 0.2022i  -0.0676 + 0.1961i

  Columns 9 through 14

  -0.0351 + 0.0257i   0.4201 + 0.0000i   0.3245 + 0.0000i  -0.2472 + 0.1952i  -0.2472 - 0.1952i   0.4502 + 0.0000i
   0.2261 + 0.0776i   0.3907 + 0.0000i   0.1499 + 0.0000i   0.1371 + 0.0300i   0.1371 - 0.0300i   0.1546 + 0.0000i
  -0.3219 - 0.1848i   0.0692 + 0.0000i  -0.1644 + 0.0000i   0.0266 - 0.0711i   0.0266 + 0.0711i   0.3148 + 0.0000i
```


MATLAB R2015a
Command Window
New to MATLAB? See resources for Getting Started.
Columns 9 through 14
-0.0351 + 0.0257i   0.4201 + 0.0000i   0.3245 + 0.0000i -0.2472 + 0.1952i -0.2472 - 0.1952i   0.4502 + 0.0000i
0.2261 + 0.0776i   0.3907 + 0.0000i   0.1499 + 0.0000i   0.1371 + 0.0300i   0.1371 - 0.0300i   0.1546 + 0.0000i
-0.3219 - 0.1848i   0.0692 + 0.0000i -0.1644 + 0.0000i   0.0266 - 0.0711i   0.0266 + 0.0711i   0.3148 + 0.0000i
0.1907 + 0.0539i -0.3216 + 0.0000i -0.1882 + 0.0000i   0.0218 + 0.2015i   0.0218 - 0.2015i   0.3503 + 0.0000i
-0.1639 - 0.0938i -0.0438 + 0.0000i -0.0302 + 0.0000i -0.1965 + 0.0210i -0.1965 - 0.0210i -0.0477 + 0.0000i
-0.0514 + 0.2219i -0.1772 + 0.0000i -0.3967 + 0.0000i   0.0628 - 0.1533i   0.0628 + 0.1533i   0.1073 + 0.0000i
0.1023 - 0.1099i -0.1510 + 0.0000i -0.0474 + 0.0000i   0.2397 - 0.1907i   0.2397 + 0.1907i -0.1253 + 0.0000i
0.1515 - 0.3017i   0.0951 + 0.0000i   0.3339 + 0.0000i -0.0790 - 0.0709i -0.0790 + 0.0709i -0.4144 + 0.0000i
0.5208 + 0.0000i   0.0772 + 0.0000i   0.0777 + 0.0000i   0.3580 - 0.0991i   0.3580 + 0.0991i -0.1909 + 0.0000i
-0.1980 - 0.0092i -0.2540 + 0.0000i -0.3225 + 0.0000i   0.2467 + 0.0762i   0.2467 - 0.0762i -0.4235 + 0.0000i
-0.2270 + 0.1521i   0.4729 + 0.0000i   0.2729 + 0.0000i -0.4506 + 0.0000i -0.4506 + 0.0000i   0.0442 + 0.0000i
-0.0340 + 0.2645i -0.1235 + 0.0000i   0.0527 + 0.0000i   0.2321 - 0.1374i   0.2321 + 0.1374i -0.3265 + 0.0000i
-0.1358 + 0.1487i   0.0564 + 0.0000i   0.3981 + 0.0000i -0.3621 + 0.0797i -0.3621 - 0.0797i   0.0856 + 0.0000i
-0.0676 - 0.1961i -0.4301 + 0.0000i -0.4382 + 0.0000i -0.0853 + 0.1935i -0.0853 - 0.1935i   0.1369 + 0.0000i
eigen_values =
Columns 1 through 8
14.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i
0.0000 + 0.0000i -0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i
0.0000 + 0.0000i   0.0000 + 0.0000i -0.0000 - 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i
0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i -0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i


MATLAB R2015a
HOME
PLOTS
APPS
Search Documentation
New Script
New
Open
Find Files
Compare
FILE
Import Data
Save Workspace
New Variable
Open Variable
Clear Workspace
VARIABLE
Analyze Code
Run and Time
Clear Commands
CODE
Simulink Library
SIMULINK
Layout
Preferences
Set Path
Parallel
ENVIRONMENT
Help
Community
Request Support
Add-Ons
RESOURCES
C: ▸ Program Files ▸ MATLAB ▸ MATLAB Production Server ▸ R2015a ▸ bin ▸
Current Folder
Command Window
New to MATLAB? See resources for Getting Started.
eigen_values =
Columns 1 through 8
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ENG
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27/10/2015